

## **Mechanical behavior of materials**

**Dr. Niraj Mohan Chawake**

**Department of Materials Science and Engineering**

**Indian Institute of Technology, Kanpur**

**Week-9**

**Lecture-47**

**Precipitation hardening and Dispersion strengthening**



**Mechanical Behavior of Materials (Hindi)**

**Precipitation hardening and Dispersion strengthening**

•

Namaskar phir se swagat karta hoon aapka is course mein jo ki mechanical behavior of materials se aur hum isko hindi mein padhenge last part tak humne dekha strain hardening kya hoti hai aur solid solution strengthening kya hoti hai ye do hardening mechanism humne dekhe is part mein hum dekhenge ki precipitation hardening aur dispersion strengthening kya hoti hai jab main is precipitation hardening ki baat karta hoon to sabse pehle mere man mein khayal aata hai aeroplanes ka kyunki jo agar main aeroplanes ki baat kar raha hoon aapko pata hi hoga humne ek fuselage ki baat ki thi aeroplane ki to yeh jo body hai aeroplane ki yeh kuch is alloy se banti hai yeh aluminium alloy hai aur yeh aluminium alloy kuch is tarah se hai iska microstructure mein dekhunga to yeh microstructure mein mujhe kuch precipitates dikhte hain to aap dekhenge ki mere paas yahan par grains hai aur grains ke andar kuch precipitates hai aur boundary par bhi kuch precipitates hai to yeh jo aluminium alloy hai yeh aluminium alloy sabse pehle socha gaya tha Alfred Wilm dwara Alfred Wilm ye ek German metallurgist tha jisne ek alloy ki invention ki kiya tha jiska naam hum Duralumin karke jaante hain ye kaafi prasiddh alloy hai aur yeh jo alloy hai yeh aluminium aur

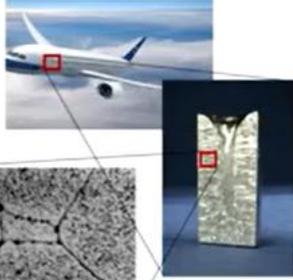
kuch percentage of copper magnesium aur manganese se banta hai aur yeh aircraft industry mein sabse jyada banta hai to Alfred Wilm jo the woh aluminium alloys par kaam kar rahe the aur yeh acche metallurgist the in inko pata tha ki jab main gamma iron ko quench karta hoon to martensite milta hai to unhone acche se kaam kiya tha austenite jo main quench karne ke baad martensite milta hai aur jo strengthening milti hai mujhe martensite dwara in ideas ke baare mein wo kaafi acchi tarike se jaante the to yeh same idea wo aluminium alloys par apply kar kar rahe the aur jab wo aluminium alloys ko quench kar rahe the tab unhe koi appreciable microstructure change ya increase in hardness nahi mil raha to ek fine saturday ek shanivaar ko unhone ek aluminium alloy quench kar diya aur weekend hone ke kaaran woh uska hardness lena bhool gaye ya unhone chhod diya aur jab unhone monday aake is aluminium alloy ka hardness check kiya to unhone paaya ki is aluminium alloy ka hardness badh gaya tha to unhone socha iske baare mein ki hardness kyun badh raha hai to ek hi cheez ho sakti hai ki weekend par unhone chhod diya tha yaane time factor unhone de diya tha tab unhone kya kiya kuch aluminium alloys quench kiye aur phir time ke saath unhone hardness measure karna chalu kiya aur tab unhe pata chala ki time ke saath unhe hardness badhte hue mil raha hai isko hum Serendipity kehte hain research mein scientific research mein to unhone paaya ki time ke saath hardness badh raha hai aur kis tarah se hardness badh raha hai agar main aluminium alloy ko quench karta hoon aur kuch samay ke liye chhod deta hoon aur uske baad agar hardness measure karna chalu karta hoon ek do din ek din ke baad do din ke baad paanch din ke baad 10 din ke baad to aapko kuch is tarah se variation milega yaani jaise jaise wo alloy age ho raha hai uske saath hardness kis tarah se variation ho rahi hai is phenomena ko hum kehte hain Age Hardening aur yeh jo time dete hain hum jahan par hamara hardness change ho raha hai usko kehte hain hum Aging Time to ye unhone paaya tha aluminium copper magnesium alloy jo ki ye Duralumin alloy jisse uski utpatti hui thi abhi hum ye jaan jaante hain ki ye age hardness ya aging jo ho raha hai yeh hardness kyun badhta hai to hum dekhenge ki ismein precipitation ka kya role hai to pehle jaante hain ki microstructure mein precipitates dikhte kaise hain.

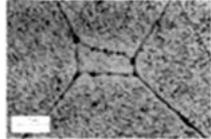


## Precipitation hardening



**Alfred Wilm**  
(25 June 1869 - 6 August 1937)  
A German metallurgist  
Invented the alloy Al- 3.5 - 5.5% Cu-Mg-Mn,  
known as **Duralumin**  
used extensively in aircraft





Al alloys

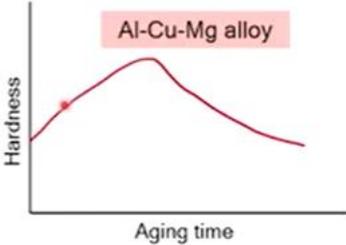
Ideas from  $\gamma_{Fe} \xrightarrow{\text{quench}} \text{martensite}$

Quenching: Al alloys

No change in the microstructure and increase in hardness

Serendipity

With time hardness was found to increase



**Al-Cu-Mg alloy**

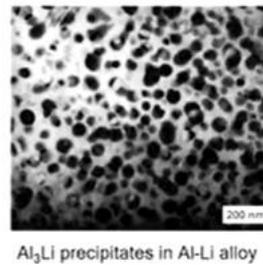
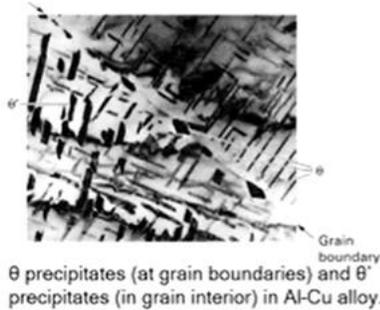
The Discovery of Strong Aluminum, Advanced Materials & Processes, August 2011  
<https://www.phase-trans.msm.cam.ac.uk/>

To yahan pe ek aluminium copper alloy maine dikhaya hai aur aap dekh rahe honge ki yahan pe kuch precipitates hai microstructure mein to yahan pe  $\theta$  precipitates hai jaise ki grain boundaries pe  $\theta'$  Precipitates hai jo interior mein dikh rahe hain to ye kuch aluminium copper system mein

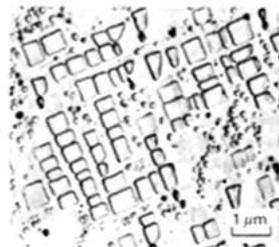
mujhe precipitates milte hain usi tarah aluminium lithium alloys mein agar main dekhunga to ye  $Al_3Li$  ye ek precipitate aluminium alloys mein ye alloy bhi light weight alloys mein ya gina jaata hai aur yeh light weight alloy aircraft industries mein kaafi acche se istemal hota hai iska uske baad humne aur ek phase padha tha gamma prime phase jisko humne dekha tha ki woh  $Ni_3Al$  phase hai yeh humein nickel base superalloys mein milta hai aur iska microstructure kuch is tarah se dikhta hai yahan pe jo cuboidal precipitates dikh rahe hain yeh saare gamma prime phase hai ya  $Ni_3Al$  hai to yeh mostly jo precipitates hai yeh yahan pe intermetallic phases hai aap dekh paa rahe honge yeh jo phases hai yeh saare intermetallics ya ordered phases hai jab hum intermetallics ya ordered phases ki jab baat kar rahe the tab humne dekha tha ki ye jo intermetallics ya ordered phases hai hamari strength badhate hain.



## Precipitates in different alloy systems



*intermetallics  
ordered phases*



To aaiye jaante hain ki ye precipitates microstructure mein kya role play karte hain to sabse pehle dekhte hain ki pehle precipitation hardening ke liye ya age hardening ke liye mujhe alloy kis tarah se prepare karna hai to pehle jaante hain ek basic understanding jab main kuch ek alloy banana chahta hoon jahan par main A mera solvent hai aur B mera solute hai yaani main B ko A mein dissolve karne ki koshish kar raha hoon to aur temperature ke saath mein kuch phase diagram dekhta hoon to maan lete hain ki yeh jo A aur B system bana rahe kuch eutectic system bana rahe is tarah se aur main yahan par abhi kuch phase fields mark karunga maan lete yeh mera liquid hai yeh alpha phase hai ye alpha plus beta phase ho jayega yeh alpha plus liquid phase ho jayega aur abhi dekhte hain ki hum precipitates is system mein milne ke liye kya process ki processes hum kya employ karna padega humein kya processes dene padenge to maan lete mere paas ek composition hai  $C_0$  Yaani yeh composition hai yahan par mera kuch weight percentage of B hai to hum dekh paa rahe hain ki yeh A rich side par hai yaani yahan par A jyada hai to yeh A rich side ho gaya yahan par hum dekhenge ki kuch A rich side idhar likh lete hain A rich side pe main hoon aur abhi ye composition ko main kuch heat karunga yaani isko garam karunga ya is temperature ke saath aage badhunga to aap dekh sakte hain is alloy mein yeh jo line hai isko kehte hain Solvus line aur yeh jo solvus line hai aap dekh paa rahe honge ki jaise jaise main temperature increase karunga waise waise B ki solubility A mein badhti jayegi to solvus line mujhe dikhata hai ki temperature ke saath B ki solubility A mein badhegi ya agar main temperature decrease kar raha

hoon to B ki solubility A mein ghat-ti jayegi to solvus line mujhe yeh darshaati hai yeh solubility darshaati hai mere B ki A mein aur yeh sab dono solid state mein hai yahan pe koi liquid phase nahi ban raha hai to dono solid state mein hai.

Abhi hum dekhte hain jab main composition ko is solvus line ke upar heat karta hoon ya is temperature par pahunchta hoon to kya changes aane chahiye to yahan par jab mujhe precipitation hardening chahiye tab teen steps important hai pehli hai Solution Treatment dusri hai Quenching aur teesri hai Aging to solution treatment yaani yeh jo phase hai yahan par aap dekhenge ki main yeh do phase region mein hoon yahan par alpha plus beta phase hai aur jab main isko heat karunga aur yeh solvus line ko cross karunga to main ek single phase region pe pahunch jaunga isi process ko hum kehte hain solution treatment to agar mujhe precipitates chahiye to yahan pe mujhe yeh solution treatment karni padegi aur yeh precipitates mujhe is tarah se chahiye ki woh jinka distribution mere hisaab se ho agar aap yahan se directly quench karenge ya kuch random heat treatments karenge to jo phase distribution milega yahan pe mujhe woh mere hisaab se nahi hoga to isko bhi hum samjhenge ki kis tarah se heat treatment karte hain to maan lete hain main yahan pe abhi phir heat treatments decide karunga to abhi main is alloy ko heat karunga is solvus line ke upar kuch is tarah se yeh  $T_0$  Temperature pe main pahunch gaya to aap dekh paa rahe honge ki yahan pe mere paas sirf alpha phase hoga isko main kehta hoon solution treatment to yahan pe microstructure main draw karunga to mere paas kuch bade grains rahenge alpha ke aur yeh saara jo B hai yaani jo solute hai wo pura is alpha mein dissolve ho jayega abhi main is se main direct quench karta hoon yaani main is temperature par gaya kuch samay ke liye ruka isko main solution treatment kahunga aur abhi maine quench kar diya kuch is tarah se is  $T_1$  Temperature tak jab main quench karunga to mujhe kuch microstructure is tarah se milega quench mein bhi par abhi hum dekhenge is temperature pe  $T_1$  Temperature pe yahan par B ki solubility kam hai as compared to is temperature pe to agar B ki solubility kam hai par maine suddenly quench kiya is phase ko to yahan pe diffusion ke liye time nahi milega aur yeh jo alpha jo grains honge ismein mere B ki solubility waise ki waise rahegi jyada rahegi to isko hum kehte hain Supersaturated Solid Solution isko bhi likh lete hain yeh ho gaya mera ye jo alpha SS hai ye mera supersaturated solid solution hoga supersaturated solid solution yaani mera B ka content is phase mein abhi jyada hai actually equilibrium diagram se hum dekh paa rahe hain ki B ka content kam hai is temperature mein par maine quench kar diya isliye is alloy ko time nahi mila B ko diffuse out karne ke liye to yahan pe hum dekhte hain ki mere paas jo solution hoga wo supersaturated solid solution hoga.

Abhi main quenching ke baad aging try karunga yaani agar main temperature ya time ke saath aging kar sakta hoon agar main is alloy ko is temperature par lambe samay ke liye chhod dunga to wo bhi ek aging hai agar main isko expedite karna chahta hoon yaani jo precipitate kyunki yahan par jo yeh jo supersaturated solid solution hai woh stable nahi hoga aur yahan se mere jo precipitate taiyaar ho jayenge to main agar isko jalad gati se karna chahta hoon ya expedite karna chahta hoon to main is temperature par usko heat karunga aur yaani is temperature se kam rahega par is room temperature se ya  $T_1$  Temperature se thoda jyada temperature rahega is temperature par main aa gaya aur is temperature par main kuch samay ke liye chhod dunga isko main kehta hoon aging to iske wajah se kya hoga temperature aur time ki wajah se mere beta ke precipitates yahan par kuch is tarah se form hone chalu ho jayenge wo nucleate honge aur grow honge to aapko yahan par kuch is tarah se precipitates milenge beta ke alpha ke grains mein kyunki yahan pe jo B ka yahan pe aap dekhenge ki ye supersaturated solid solution hai ye decompose hoga alpha aur beta mein kyunki yahan pe stable phase mere paas kya hai alpha aur beta to phir main kuch lambe samay ke liye chhod dunga to aap dekhenge ki yeh jo precipitates hai ye grow honge yaani inka size badhega aur

number density inki hai woh ghategi aap dekh paa rahe honge yahan pe yeh precipitates beta ke precipitates jyada hai numbers jyada hai aur is case mein inka size badh gaya hai par number density kam ho gayi hai to aap dekh paa rahe honge ki main microstructure ko main tune kar sakta hoon yaani main apne hisaab se usko design kar sakta hoon jab main aging time ya temperature ke saath usko process karta hoon to main temperature aur time control karke yeh precipitates ki size aur distribution aur aap dekh paa rahe honge ki in jo precipitates ka distance jo hai yahan pe yeh bhi ek important cheez hai aspect microstructure yeh jo distance hai aur yahan ka distance hai aap dekh paa rahe honge ki jo average distance hai precipitates ka yahan pe kam hai aur average precipitates ke beech ka distance jo hai yahan pe jyada hai ye jo process hai longer time pe jo hoti hai isko hum kehte hain Ostwald Ripening to aap dekh rahe honge ki smaller jo precipitates hai wo consume ho jayenge bigger precipitates form hone ke liye isko hum kehte hain Ostwald ripening to is tarah se main microstructure mein precipitates prapt kar sakta hoon agar mere paas kuch is tarah se phase fields available hai to.

## Precipitation hardening

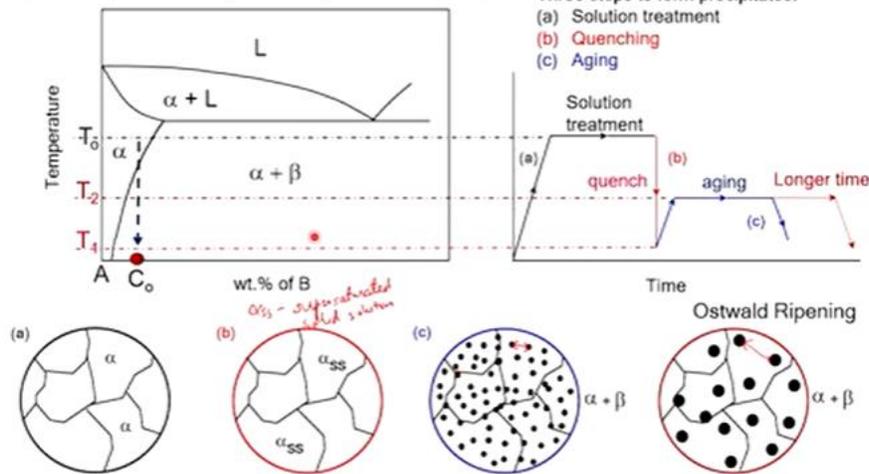
Basic criteria to obtain precipitation hardening (age hardening):

The solvus line should decrease with decrease in temperature  
(decreasing solid solubility as the temperature decreases)

Three steps to form precipitates:

- (a) Solution treatment
- (b) Quenching
- (c) Aging

*A Bich*



Abhi hum dekhte hain ki precipitates mein is case mein kya kya stages ho sakti hai aur is precipitates ka is stages ka precipitates ke nature par kya asar hota hai to mere paas pehle supersaturated solid solution tha phir wahan par kuch transition phases taiyaar honge phir mere paas kuch aged phase taiyaar hoga isko hum samajhte hain to yahan pe main aluminium copper alloy ka example lena chahta hoon to mere paas ek supersaturated solid solution phase main le loonga alpha alpha SS bhi likh sakta hoon yahan pe isko main alpha SS tha aur is supersaturated solid solution ko jab maine quench kiya aur kuch time ke liye age kiya to mere paas sabse pehle taiyaar hoga GP Zones isko kehte hain Guinier Preston zone aur phir ye Guinier Preston zone transform hoga  $\theta''$  Mein phir transform hoga  $\theta'$  Mein aur finally ek phase milega mujhe  $\theta$  jo ki  $Al_2Cu$  phase hai mera to yeh mera aged phase hai kuch is tarah se to yeh beech ke steps hai yahan pe ya different stages hai mere precipitation ke to sabse pehle mujhe Guinier Preston zone milta hai aur inko main dekhta hoon ismein precipitates kis tarah se rehte hain to aap dekh paa rahe honge ki mere paas jo precipitate yahan par taiyaar ho raha hai sabse pehle aging time ke saath wo GP zones taiyaar ho rahe hai aur yeh jo precipitates honge yeh bahut fine honge ya small size

honge aur yeh completely coherent honge completely coherent ya aap dekh paa rahe honge ki yeh mera precipitate yahan par aur yeh mera matrix hai to jo lattice planes hai in inmein jo matching hai precipitates aur matrix mein dono mein yaani equal matching hai yahan par ya koi mismatch nahi hai yahan par lattice planes beech mein kisi bhi side par to to is type ke precipitates ko hum kehte hain complete coherent precipitates aur yeh GP zones mein humein milte hain to ye ek type ka precipitate ho gaya mere paas aur agar main kuch samay ke liye aur chhod doon to ye GP zones transform honge  $\theta'$   $\theta''$  Mein aur yeh hote hain  $\theta''$  Mein transform kuch is tarah se to  $\theta''$  Mein jab transform honge to aap dekh paa rahe honge ki ye yahan pe coherent precipitate hai yahan pe bhi matching ho rahi hai meri precipitates aur matrix ke lattice planes ke beech mein par aap dekh paa rahe honge ki matrix ke jo planes hai woh stretch hai yeh jo coherency maintain karne ke liye yeh jo plane stretch ho gaye to inko hum kehte hain Strained but coherent precipitates yaani precipitates ki wajah se yahan pe straining ho gayi hai interface ke interface pe aur par precipitates mere coherent hai to yeh milta hai mujhe  $\theta''$  Pe aur yeh jo mera actual microstructure hai schematics hai abhi hum semi coherent precipitates dekhte hain to yeh  $\theta'$  Hote hain aur yeh  $\theta'$  Jab main dekhunga to aap dekh paa rahe honge yahan par mera jo precipitate hai yeh semi coherent hai semi coherent yaani kya hai agar yeh interface main dekhunga yahan par matrix aur precipitate ke beech mein jahan pe perfect lattice matches hai to yahan pe aap dekh paa rahe honge kuch planes match hai kuch planes match nahi hai isliye isko hum semi coherent kehte hain agar ye plane main consider karu aur ya ye plane consider karu ye dono matched hai yahan pe agar plane consider kar ye matched hai ye plane consider karu to ye matched hai ye plane consider karu to ye matched hai par ye plane agar main consider karu ye wala ya ye wala to aap dekh paa rahe honge ki ye matched nahi hai aur main in planes ko is tarah se bhi samajh sakta hoon ki ek extra half plane hai yahan pe inserted to yeh jo interface yahan par taiyaar hoga yahan par coherent hai par yahan par semi coherent hai to yeh jo precipitate hai ye semi coherent hai aur aap dekh paa rahe honge ki ye jo dislocations yahan pe inko coherency dislocations kehte hain aur kuch is tarah se mujhe yeh coherency dislocations mujhe is  $\theta'$  Precipitates pe milte hain abhi hum dekhenge incoherent precipitates to hum  $\theta'$  Tak aaye aur  $\theta$  jab banega tab aap dekhenge ki matrix aur precipitates hai wo mismatched hai yaani ismein koi coherency hai nahi dono planes dono lattice aur precipitates alag alag hai unka spacing alag alag hai to isliye 100 percent mismatch hai yeh kehte hain isko kehte hain hum incoherent precipitates to yahan pe humne alag alag nature of precipitates ki baat ki hai abhi aap dekh rahe honge ki main magnification agar yahan par dekhun to ye precipitates GP zones hai yeh bahut chhote hain agar mujhe isko dekhne ke liye ek high magnification par jaana pad raha hai aur incoherent precipitates inko dekhne ke liye main 8000x pe hi main inko dekh paa raha hoon to aap dekh paa rahe honge ki yahan se GP zones se  $\theta'$   $\theta''$   $\theta'$  Aur  $\theta$  tak yeh jo size hai precipitates ke badh rahe hain to main do observation yahan par likh sakta hoon ki mere Size of Precipitates badhte hain main jab alpha supersaturated solid solution ke precipitation ke sequence ko dekhunga to yeh jo size hai precipitates ka badh raha hai aur humne dekha tha ki inke beech ka distance bhi badhega aur abhi hum dekhenge jo interface hai yeh bhi change ho raha hai yaani main GP zones mein hoon to mere paas coherent interface hai main agar  $\theta''$  Mein hoon to yahan pe bhi coherent hai par strained interface hai  $\theta'$  Mein hoon to semi coherent interface hai aur agar  $\theta$  pe hoon to mere paas incoherent precipitates hai abhi hum dekh paa rahe honge ki size bhi yahan par badh raha hai aur interface bhi change ho raha hai iske wajah se kya hoga yeh jo precipitates hai mere dislocation ke saath alag tarike se interact karenge to abhi hum dekhte hain ye humne precipitation study kiya abhi inka influence dekhenge dislocation ke upar kaise hota hai to hum jab strength ki baat karte hain strength ki baat karte hain to yahan par hum jab baat kar rahe to jab mere dislocation ko main rokta hoon ke motion ko rokta hoon tab mujhe strengthening milti

hai to yeh precipitates exactly wahi karte hain yeh dislocations ki motion ko rokhte hain ya jab unke motion mein unko unke motion ko cause karne mein jo energy lagegi unko badhate hain to do possibilities ho sakti hai ek to dislocation bypass ho sakta hai mere precipitates ke saath ya dislocation un precipitates ke through pass ho sakta hai ya unko shear kar sakta hai ya cut kar sakta hai to hamare paas do mechanism hai ab in dono mechanism ko hum padhte hain.

## Different stages of precipitation

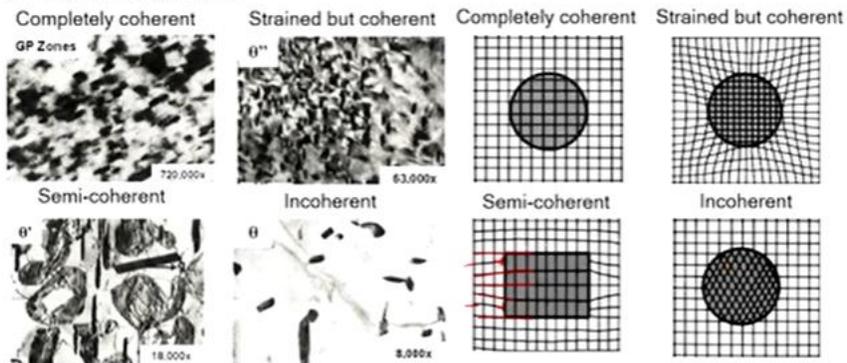
During aging, the precipitation takes place in the following sequence:

Supersaturated solid solution → Transition structures → Aged phase

Al-Cu alloys  $\alpha_0 \rightarrow GP \rightarrow \theta'' \rightarrow \theta' \rightarrow \theta (Al_2Cu)$

- The size of the precipitates increases and distance between them increases
- Interface of precipitates change

GP: Guinier-Preston zone



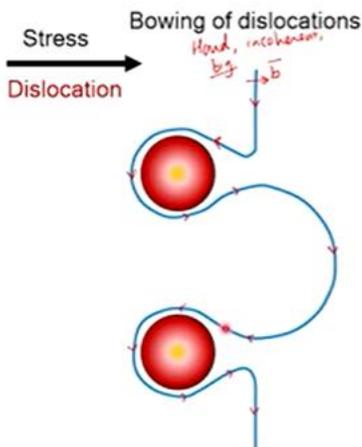
Phase Transformations in Metals and Alloys: Porter, Easterling, (2009) Mechanical behavior of materials, Meyers & Challa

## Precipitate-dislocation interactions

Two possibilities

Dislocations bypass the precipitate

Dislocations pass-through (shear/cut) the precipitate

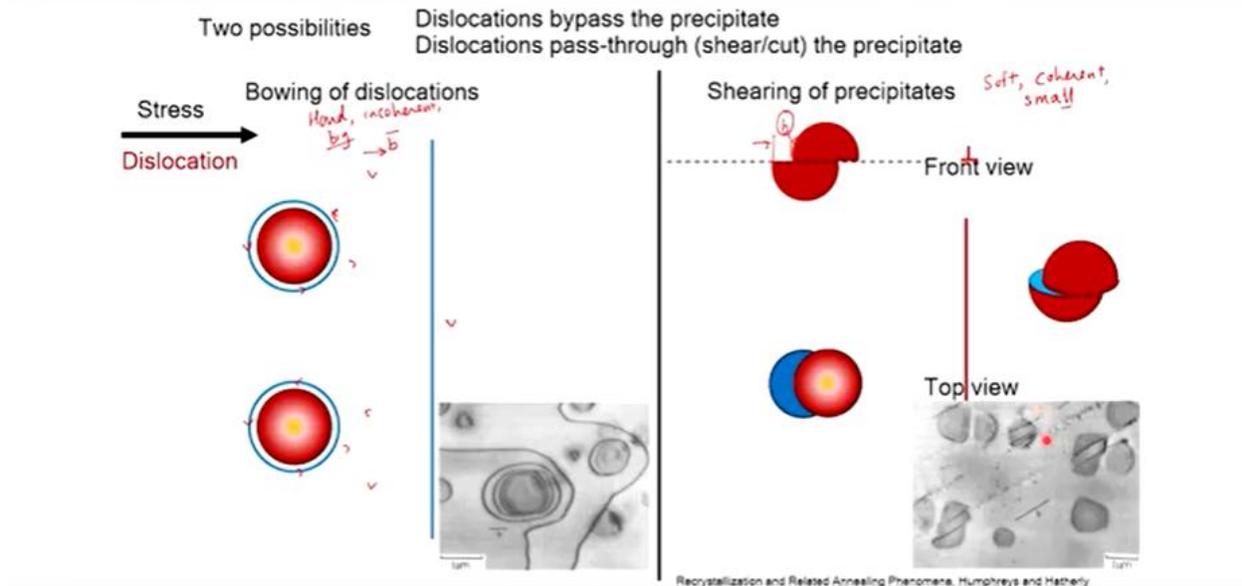


Pehle hum dekhte hain ki bypass of the precipitate isko bhi Bowing of Dislocations kehte hain abhi maan lete hain mere paas ek dislocation hai ek kisi slip plane pe hai aur main stress apply karta hoon aur mere paas kuch is tarah se precipitates hai abhi jab dislocation stress ke andar move

karega is direction mein to aap dekhenge ki yeh jo precipitate is dislocation ko rokenge pehle to is dislocation ko rokenge tab mere material ki strength badhni chahiye kyunki mujhe aur high stress chahiye hoga is dislocation ko move karne ke liye is plane pe to yeh movement kaise hoti hai hum dekhte hain to maine agar high stress apply kiya to ye dislocation yahan se move hoke yahan tak aa gaya aur yahan pe ruk gaya kyunki yeh precipitate yahan par hai aur yahan par hai to agar main is dislocation ko is plane pe move karne ke liye further to mujhe stress badhana padega to meri strengthening ho rahi hai yahan pe material ki to main stress jab badhata hoon to dislocation kuch is tarah se bow honge kyunki inki size badi hai aur yeh incoherent precipitate hai is conditions ko main likh leta hoon yeh milta hai mujhe Hard Precipitate aur Incoherent precipitate jab rahenge ye aur ek point yahan par likh sakta hoon ya bade rahenge Big Precipitates ye teen condition jab rahegi tab yeh press ye dislocation hai yeh yahan par is tarah se bow hoga agar main isko aur stress apply karu to mere paas kuch is tarah se configuration aa jayegi dislocation ki humne dekha tha ki dislocation is tarah se bow hote hai aur yeh bowing ke liye mujhe ek stress apply karni padegi to ye stress jo apply karni padegi wo depend karegi mere yeh jo particle hai ya precipitates ke distance hai inke distance ke upar ye depend karegi yaani agar ye distance jyada hai to mujhe stress jo lagega woh kam lagega aur distance kam hai to is bow karne ke liye stress jyada lagega abhi kya hoga agar main continuously stress badha raha hoon to ye dislocation aur bow hoga abhi hum kya karte hain is dislocation ki analysis karte hain agar main tangent vector mark karta hoon kuch is tarah se to tangent vector is tarah se ja raha hai aur kuch is tarah se ja raha hai tangent vector kyunki tangent vector to current ki tarah jaata hai to is tarah se humein milega abhi aap dekhenge kuch is tarah se ye position pe ya ye position pe aap dekhenge ki jo nature ban raha hai dislocation ka agar Burgers vector main kuch is direction pe maanu aur Burgers vector humne dekha hai ki wo ek invariant hai mere ek dislocation line ke liye to yahan pe jo nature banega dislocation ka kyunki tangent vector is side ja raha hai opposite side aur ye tangent vector iske opposite side ja raha hai aur Burgers vector same rahega to to yahan pe opposite nature of dislocation taiyaar honge similarly yahan pe jo dislocation taiyaar ho rahe hai yahan pe jo nature aap dekhenge yahan pe ye jo dislocation ka tangent vector is side hai aur yeh jo dislocation yahan pe dikh raha hai iska tangent vector is side hai to dono opposite nature honge aur ek dusre ko attract karenge aur attract karke kya hoga ye dislocation ek dusre ko attract karke annihilate karenge aur is precipitate ke around ek loop taiyaar karenge aur yeh dislocation phir mukt ho jayega yaani free ho jayega aur is tarah se yeh aage badhega to abhi hum dekhte hain ki aage ka step kaise hota hai to yeh is tarah se loop banega aur yeh dislocation is tarah se free ho jayega to humne dekha ye bowing kya hota hai yahan par dislocation bow hua is tarah se aur yahan par jab wo free ho gaya tab yahan par ek loop taiyaar ho gaya mere precipitate ke around to yeh dislocation loop is tarah se ho gaya aur yeh dislocation yahan par free ho gaya is slip plane par move hone ke liye abhi agar aage agar koi dislocation yahan se aata hai to yeh dislocation aake is precipitate ke saath phir se interact karega is tarah se aur aap dekh paa rahe honge ki yahan par ek loop taiyaar ho gaya to yeh jo distance hai in dono ke beech ka woh ghat gaya hai kyunki is loop mein kuch elastic interactions honge mere dislocation ke saath to aap dekhenge ki yeh dislocation jab bow karega next time to usmein mujhe jyada stress apply karna padega to yeh ho gaya mera bowing of dislocation aur isse mere material ki strength badhti hai yeh kab milta hai mujhe jab mere precipitate hard hai incoherent hai aur bade hai abhi dusra mechanism dekhte hain jahan par dislocation pass through karte hain shear karte ya cut karte mere precipitate ko to abhi main Shearing of Precipitates consider karunga ye humein milta hai exactly opposite case mein jahan pe mere precipitates hai Coherent hai aur Small hai agar ye teen conditions hai to mera dislocation precipitate ko shear kar sakta hai.



## Precipitate-dislocation interactions



To maan lete hain ye mera precipitate hai ye mera front view is tarah se ye mera slip plane hai yahan pe yahan pe dislocation move ho raha hai aur ye top view hai kuch is tarah se to jab ye dislocation yahan pe aayega to ye yahan tak aayega aur is precipitate se interact hoga stop ho jayega to aap dekh paa rahe honge yahan par bhi jab dislocation ki motion ruk jayegi to strength meri badhegi abhi main kya karunga abhi main kuch extra stress apply karunga aur yeh dislocation is precipitate ke through cut ho jayega kyunki yahan par humne dekha tha ki coherent precipitates mein jo slip planes hai ya koi lattice mismatch nahi hota hai to dislocation is plane pe continue kar sakta hai move karna to isliye jab mere paas coherent precipitate hai chhote hain aur soft bhi hai tab ye dislocation usi slip plane par continue kar sakte aur uske wajah se kya hoga yeh precipitate jo hai shear ho jayega shear yaani cut hoga abhi usko hum dekhte hain ki kis tarah se wo cut hoga to yeh kuch is tarah se cut hoga jab main extra stress apply kar raha hoon to yeh mere precipitate ko cut karega aur kuch extra surface yahan pe banega to yeh jo cutting mechanism hai mere precipitate ki is mechanism mein bhi mere dislocation ko kuch extra energy lagegi aur iske wajah se mere material mein strengthening hogi to ye jo step yahan pe hum dekh rahe hain ye jo step yahan pe banta hai ye step banta hai mere dislocation ke Burgers vector yaani yeh matrix ka jo dislocation hai uska jo Burgers vector hoga utna step is precipitate pe humein dikhega to ye mera front view hai top view hai abhi hum isko 3D view mein kuch is tarah se dekh sakte hain to aap dekh paa rahe honge ki mera precipitate is tarah se shear ho gaya ya cut ho gaya aur main keh sakta hoon ki dislocation pass through ho gaya mere precipitates to ye jo blue color ka plane dikh raha hai yahi mera slip plane hai iske upar mera dislocation move hua hai to abhi yeh schematically humne yeh dekha hai do mechanism jahan par dislocation bypass ho sakta hai ya cut ho sakte hain shear ho sakte hain wo depending mere precipitate ka nature kya hai to microscopic bhi hum kuch is tarah se dekh sakte hain yahan par kuch TEM micrographs maine dikhaye yahan par aap dekh sakte hain ki dislocation yahan pe bow ho rahe aur yahan par kuch dislocation loops taiyaar ho rahe hain mere precipitates ke around aur yahan par aap dekh sakte hain ki dislocation shear through ho raha hai yahan pe aap dekh sakte hain yahan par do baar shear ho chuke hai yahan pe dislocation pass ho gaya aur yahan pe bhi dislocation pass ho gaya slip planes pe to aap dekh sakte

ho ki mere precipitates is tarah se kuch shear ho rahe hain ye yahan par kuch mark hai to yeh jo do mechanism hai inko do naam diye hain to pehle mechanism ka jahan par dislocation bow hua usko hum kehte hain Orowan Mechanism ya Orowan Looping dusra mechanism hai Shearing Mechanism to yeh dono mechanism hum dekhte hain jab precipitates ke size ya nature change hote hai abhi humne dekhe shearing aur cutting of precipitates kab hota hai small aur soft aur coherent precipitates hai tab aur dislocation bypass kab hota hai ya bowing kab hota hai jab mere paas big hard aur incoherent precipitates hai abhi hum jab baat karte hain precipitates ki tab mere paas unke nature bhi hai jaise precipitates coherent ho sakta hai semi coherent ho sakta hai aur incoherent ho sakta hai to hum dekhte hain ki jo coherent precipitates hote hain wo small precipitates hote hain humne dekha tha ki GP zone small hote hain to ye small precipitates hote hain generally aur semi coherent precipitates wo intermediate size precipitates hote hain aur incoherent precipitates hain wo large precipitates hote hain to humne kuch is tarah se padha tha aluminium copper system ko lekar hamare paas alpha supersaturated solid solution tha jo GP zone mein transform hua phir hamare paas  $\theta'$  Phir  $\theta''$  Phir  $\theta'$  Aur phir humein  $\theta$  to yahan par hum incoherent precipitates ki taraf badh rahe hain to yahan par bhi dekhenge size jo hai is direction mein badh raha hai aur coherency yahan pe loose ho rahi hai yahan par mere paas coherent precipitates hai aur ye coherency is direction mein loose hoti hai ya kam hoti hai to aapke paas size yahan par badh raha hai precipitates ka aur coherency bhi change ho rahi hai to agar mere paas kuch is tarah se precipitates hai to wo dislocation ke saath differently interact karenge to aaiye dekhte hain do microstructure yahan par jab main Aged Condition ki baat kar raha hoon mere paas precipitates kuch is tarah se hai alpha plus beta humne ye dekha tha ki yahan par mere paas small precipitates hai yaani unka size small hai aur unke beech ka distance average distance bhi kam hai jab hum dekhte hain Overaged Condition mein to mere paas unka number density ghat-ti hai aur unka size badhta hai aur aap dekhenge ki unke average distance bhi badhta hai to main kuch teen factors yahan pe mark kar raha hoon Fraction of precipitates Inter-particle spacing  $R$  capital R aur Precipitate Size  $r$  to aap dekhenge ki jab main aged condition se overaged condition mein jaata hoon to  $f$  yahan pe decrease ho raha hai yeh fraction yahan pe kam ho raha hai aur aap dekhenge ki  $r$  yahan par badh raha hai yaani size badh raha hai yahan par precipitates ka aur yahan par precipitates inter-particle spacing badh raha hai yaani capital  $R$  badh raha hai yahan pe aur small  $r$  yaani precipitate size bhi yahan par badh raha hai yeh hum jab baat karenge yeh time ke saath main baat kar raha hoon ek constant temperature aur time ke saath to mera volume fraction jo hai wo kuch is tarah se badlega to yahan par main  $f$  jab baat karunga to yeh meri number density hai yahan pe numbers jyada hai yahan pe number density kam hai to jab yeh conditions aati hai to main dekhta hoon ki bypass aur shearing kab ho sakta hai tab humne dekha hai ki yahan pe jo precipitates hai ye yeh jo precipitates hai ye honge small size hai mere small yeh coherent ya incoherent ho sakte hain mostly coherent ho sakte hain aur yahan par yeh soft bhi hote hain to yeh teen condition hote aged condition mein yeh aapko dikh raha ye bade hai yeh hard ho jaate hai aur incoherent ho jaate hai size ke saath to aap dekhenge ki is case mein yahan par mujhe bowing milegi aur is case mein mujhe shearing milegi to main dekhta hoon ki aap jab bowing ki jab baat kar rahe tab dislocation curve hoga yaani hum jab baat karenge mere paas isko samajhte humne bowing dekhi thi agar dislocation is tarah se pin hai aur main stress apply kar raha hoon shear stress to iske wajah se yeh dislocation bow hoga kuch is tarah se humne dekha tha ye aur agar main kuch radius yahan pe maan lu  $R$  aur inter-particle distance  $L$  maine is tarah se calculate kiya tha aur yeh  $\tau$  ko main evaluate kar sakta hoon jab main bowing ki baat kar raha hoon yahan pe to hum ye same understanding relation hum yahan par dekhenge to main  $\tau$  ko kuch is tarah se likh sakta hoon  $\alpha Gb/R$   $R$  jo hoga yahan pe yahan pe isko correct kar lete hain yeh jo  $R$  maine radius

likha tha ya inter-particle spacing yahan par is tarah se coherency rehne to ye jo hai ye inter-particle spacing consider kar raha hoon yahan pe  $R$  to yeh humne dekha tha ki yeh jo  $\tau$  hai ye depend karta hai ki yahan par kitna distance hai pinning points ke beech mein is case mein hum consider karenge ki jo  $R$  hai ye average distance hai mera inter-particle spacing ka to ye  $\tau$  mujhe milega  $\alpha Gb/R$  abhi hum dekhenge ki yeh jo relation hai kis tarah se small  $r$  par dependent hai to agar hum dekhenge to main kuch is tarah se likh sakta hoon  $\tau$  ko is inversely proportional to  $1/r$  small  $r$  jo ki precipitate size hai kyunki  $R$  is directly proportional to  $r$  yahan par dekh rahe ki  $R$  jaise badh raha hai waise small  $r$  bhi badh raha hai to main yeh relation likh sakta hoon usi tarah se yaani particle size ke precipitate ke saath main shear stress ki dependence likh raha hoon precipitate cutting mein main direct relation likh raha hoon yahan par mujhe  $\tau$  ye directly proportional milta hai  $\sqrt{r}$ .

## Nature of precipitates: Cutting and Bowing

Dislocations Shearing or cutting of precipitates	: Small, soft, Coherent
Dislocation Bypassing or bowing precipitates	: Big, hard and Incoherent

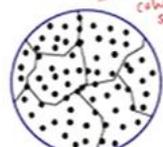
  

Coherent with the matrix	: Small precipitates (GP zones)
Semi-coherent with the matrix	: Intermediate size precipitates
Incoherent with the matrix	: Large precipitates

*Handwritten notes:*  $\alpha_{SS} \rightarrow GP \rightarrow \theta'' \rightarrow \theta' \rightarrow \theta$  (incoherent)  $\rightarrow$  size

**aged condition**

*small, coherent, semi-coherent, soft*



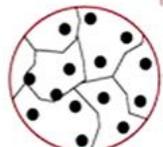
$\alpha + \beta$

*time*  $\rightarrow$  *vol. fraction*

f decreases  
R Increases  
r Increases

**Overaged condition**

*Big, hard, incoherent*



$\alpha + \beta$

Remember bowing/curved dislocation

$$\tau = \frac{\alpha Gb}{R} \Rightarrow \tau \propto \frac{1}{R} \because R \propto r$$

Increase in stress because of bypassing and shearing

Precipitate shearing

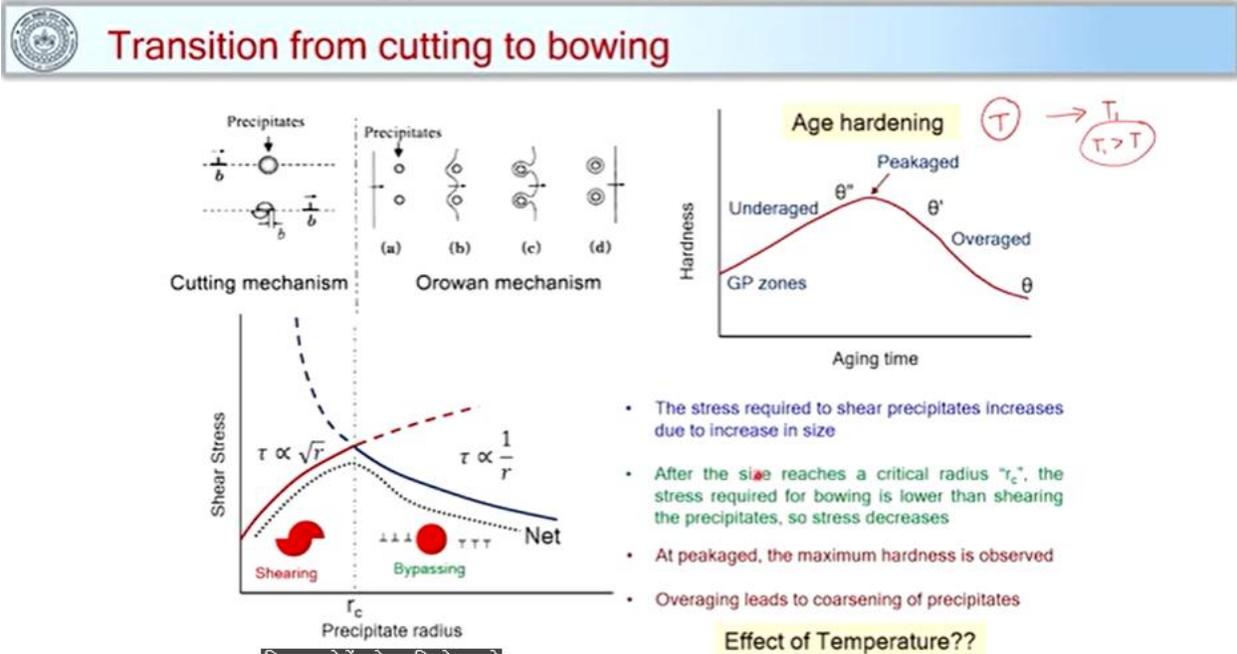
$$\tau \propto \sqrt{r}$$

Ye derivation aap kisi bhi standard physical metallurgy ke book mein dekh sakte ho yahan par main direct ye strength ka equation istemal kar raha hoon to mere paas do relation ho gaye yaani shear stress kis tarah se vary hota hai precipitate size ke saath to aaiye jaante hain ki jab main precipitation hardening ki baat karta hoon tab mere paas kab cutting milegi aur kab bowing milegi dislocations ki to humne yeh sabse pehle hamare pehle slide mein yahan par dekha tha ki hardness aur aging time ke saath to humein jab main mujhe precipitates hai to mere paas GP zone sabse pehle taiyaar honge phir  $\theta''$  Phir  $\theta'$  Aur  $\theta$  to yahan pe hum dekhenge ki mere paas  $\theta''$  Kuch is tarah se honge to ye jo condition hai yahan pe is time ke saath hum usko Underaged kehte hain yahan pe hum Peak Aged kehte hain aur iske baad isko Overaged kehte hain ye hum hardness variation ke saath kehte hain jahan par humein maximum hardness milti hai us condition ko hum peak aged kehte hain uske baad ke condition ko hum kehte hain overaged aur uske niche wali condition ko kehte hain underaged aur yeh jo hai yeh hamara age hardening curve hai to humein yeh jo nature mil raha hai hardness ka time ke saath wo kyun mil raha hai ye abhi hum samajhte hain to ye mil raha hai humein cutting aur bowing ke interplay ki wajah se to hum ye do mechanism yahan pe dekhe the ki cutting mechanism yahan pe maine dekha tha ki precipitate small hai soft hai aur coherent hai tab dislocations yahan pe isko intersect karke ya cut through ya shear through

karke ja sakte hain jab precipitates hard hai incoherent hai ya bade hai tab ye jo dislocation hai ye is tarah se bowing honge usko hum Orowan mechanism kehte hain.

Abhi main shear stress versus precipitate size ka plot karunga to aap dekhenge ki yahan pe is case mein jahan pe peak aged ke pehle mere paas underaged condition hai aur GP zones hai jo ki mere paas soft hai small size hai aur coherent precipitates semi coherent precipitates hai to yahan par jo condition hogi precipitate ki yahan par ye pehle mujhe cutting mechanism milega to cutting mechanism ka humne dekha tha ki  $\tau$  is tarah se vary hota hai directly proportional to  $\sqrt{r}$  To mujhe kuch is tarah se variation milega precipitate size ke saath jab mujhe mere paas cutting mechanism operative hai jab Orowan mechanism operative hai tab humein is tarah se milta hai shear stress ka yeh inversely proportional hai  $1/r$  ka to abhi hum dekhenge is condition mein  $\tau$  ya jab hum yeh yeh point mark kar lete yahan par yeh meri critical radius hai is critical radius ke pehle aap dekhenge ki cutting mechanism operative hai aur is critical radius ke baad meri Orowan mechanism operative hai to aap dekh paa rahe honge ki jab mere paas precipitates ke size  $r_c$  Yaani critical size se kam hai tab cutting mechanism operative hai kyun operative hai kyunki aap dekhenge ki shearing jo stress hai wo mere bowing stress ya Orowan mechanism ka jo stress hai usse kam hai aur is critical radius ke baad aap dekhenge ki bowing karne ke liye jo stress lagega wo mere cutting mechanism pe jo stress lag raha hai usse kaafi kam hai to yeh critical radius ke baad aap dekhenge ki Orowan mechanism operative ho jayega agar main overall shear stress ki plot karunga to yahan par mujhe shearing mechanism milega yahan par mujhe bypassing mechanism milega aur overall net jo shear stress mujhe lag raha hai to kuch is tarah se mujhe variation milega aur aap yeh jo nature dekh dekhenge aur yeh nature wo exactly yeh behavior darsha raha hai to aap dekhenge ki yeh jo humein nature mil raha hai age hardening curve ka jahan par humein maximum hardness milti hai wahan par hum dekh paa rahe hain ki dono mechanism mein jo stress lag rahi hai wo highest rahi hai aur jo net stress humein lagegi uske wajah se woh bhi highest rahegi to isliye humein hardness yahan par maximum milta hai aur hum shear stress ko hardness ke saath compare kar sakte hain yahan par kuch points main likhna chahta hoon jab stress required to shear precipitate increases due to increase in size yahan par ye jo point likha hai iska matlab hai jaise shear ke liye shearing ke liye yaani cut through ke liye mechanism ke liye jab main shear stress ki baat karunga yeh badhega mere particle size ke saath aur ek critical size pe ye maximum value mujhe milegi uske baad bypassing mechanism mujhe dikhega kyunki ye jo stress hai wo kam rahega mere shearing mechanism ke saath to ye ho gaye do points ye observation ke anusar abhi hum dekhte hain ki peak aged pe mujhe maximum hardness milega kyunki yahan pe dono mechanism mein jo stress lag raha hai cutting mechanism ya Orowan mechanism mein ye highest hai aur over aging mein kya hoga over aging mein hoga ki mere particle coarse ho gaye aur jaise jaise particle coarse ho gaye unke beech ka distance jo hai woh badhega aur number density kam hogi to uske wajah se jo bypassing mechanism hai woh aasaan hote jayega abhi humne to yeh time ke saath plot kiya abhi hum dekhte hain hum hum main aapko ek question puchna chahta hoon ki yeh effect temperature ke saath kis tarah se hoga yaani humne ek particular temperature pe age hardening curve dekha hai agar main dusre temperature par higher temperature par jaunga jahan par ye temperature bada hai to yeh behavior kis tarah se change hona chahiye ye aapko dhundhna hai to aapko effect of temperature mere age hardening curve par dhundhna hai ab

yeh ho gaya mera precipitation hardening.



Abhi ek aur strengthening mechanism dekhte hain jo precipitation hardening ki tarah hi hai yaani jiske jo mechanism hai wo precipitation hardening ki tarah hi hai isko hum kehte hain Dispersion Strengthening dispersion strengthening mein kya karte hain hum ki jo material hai ya matrix hai usmein ek insoluble second phase add karte hain yaani mere paas ek soft matrix hai usmein hum ek hard insoluble second phase out add karte hain to agar hum dekhenge to hum do cheezein humein mil sakte hain ek Dispersion Strengthened Metals aur hum dekh sakte hain ki hum composites bhi bana sakte hain agar main kuch foreign particle daal raha hoon mere material mein to main composite bhi bana sakta hoon usko kehte hain Particle Reinforced Metallic Composites to in dono mein difference kya hai to in dono mein difference yeh hai ki jab main dispersion strengthened metals ki baat kar raha hoon to mere volume fraction of dispersoid yaani jo second phase hai isko main dispersoid kehta hoon ye jo dispersoid ka volume fraction hai wo 3 se 4 percent hota hai woh jyada nahi hota hai woh kam hota hai isliye hum usko dispersion strengthened metals kehte hain usko composites nahi kehte par yeh jo dispersoid hai yeh mujhe composite effect dete hain ek high stiffness dete hain jo hum rule of mixture se calculate kar sakte hain to yeh difference hai agar mujhe stiffness enhance karni hai tab main particle reinforced metallic composites ka istemal karta hoon agar mujhe sirf strength increase karna hai tab main dispersion strengthened metals ka istemal karne ke liye theek hai to ye yeh jo hai particle reinforced metallic composite yeh main high stiffness agar mujhe prapt karna hai tab main inka istemal karta hoon yahan par mujhe sirf strength badhani hai tab main volume fraction jo hai mere dispersoids ka kam rakhunga to yeh jo second phase particle hai yahan par yeh hote size mein small par hard yaani hard hote hain ye aur yeh jo hai mere dislocation ki motion ko rokne hain isliye mujhe strengthening milti hai aur yeh jo mechanism hai yeh exactly jo humne bowing mechanism dekha tha ya Orowan mechanism dekha tha usi tarah se yeh second particle operate karte yahan par main likh loonga ki mujhe Orowan mechanism milega jab main dispersion strength ki baat kar raha hoon aur yeh isliye hota hai ki yahan par mere dislocation interact karenge mere particles ke saath abhi hum yeh kyun karte to dispersion strengthening ka advantage yeh hai ki hum jab precipitates ki baat kar karenge to precipitates ek high temperature par jaake dissolve ho jaate hain to humne yeh dekha tha yahan

pe phir se main ek phase diagram nikaal leta hoon ye temperature tha yeh percentage B tha aur yeh A tha aur humne ek eutectic phase diagram yahan par dekhi thi kuch is tarah se aur mere paas kuch composition yeh tha yahan pe to aap dekhenge ki ye mera composition hai  $C_0$  Agar main is temperature pe cross karunga ye temperature pe  $T_1$  Pe to aap dekhenge ki ye phase dissolve ho jayega precipitate phase dissolve ho jayega to precipitate dissolve hota hai at high temperature to main likh sakta hoon jaise main temperature badha raha hoon to dissolve honge precipitates aur meri strength jo hai woh ghategi to high temperatures par hum precipitation strengthening material istemal nahi kar sakte wo advantage humein dispersion strengthening material mein milta hai jahan par ye precipitates inert hote hain matrix ke saath saath ya dissolve nahi hote high temperatures ke upar yahan pe ek example main dena chahta hoon yahan pe mere paas kuch nickel based superalloy hai Inconel 792 ya Mar-M200 aur yahan pe ek ek Thoria dispersed nickel hai yahan pe maine kuch thoria dispersion kiya hai nickel ke andar to aap dekh paa rahe honge ki jo strength hai superalloys ki wo lower temperatures pe to jyada hai par high temperatures pe jaise jaise precipitates dissolve hona chalu karenge matrix mein waise waise strength yahan par ghategi par TD nickel yaani thoria dispersed nickel mein aap dekhenge ki strength meri at high temperature par retain ho rahi hai kyunki yeh thoria jo hai wo nickel mein nickel ke saath react nahi hota ya dissolve nahi hota hai to ye strengthening ko bhi maintain karta hai high temperature pe yahi hamara advantage hai dispersion strengthening ke saath.



## Dispersion strengthening

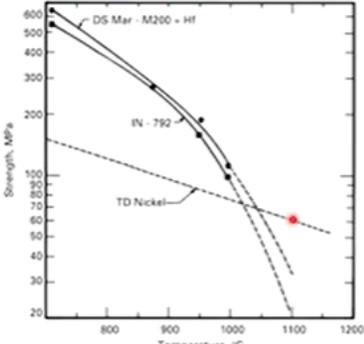
In dispersion-hardening, we incorporate hard, insoluble second phases in a soft metallic matrix.

Dispersion-strengthened metals Vs Particle-reinforced metallic composites

Volume fraction of dispersoids, 3-4%    Composite effect to achieve high stiffness

Orowan mechanism

Small, but hard, particles as obstacles to dislocation motion

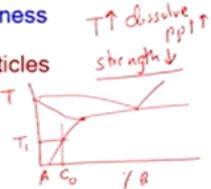


The stability of the dispersoids

Comparison of yield strength of dispersion-hardened thoria-dispersed (TD) nickel with two nickel-based superalloys strengthened by precipitates (IN-792) and directionally solidified (DS) MAR M 200

Mechanical behavior of materials, Meyers & Chawla

The interaction of dislocations with the particles



↑ Dissolve ppt ↑  
Strength ↓

To is part mein humne dekha hai do strengthening mechanism humne dekhe precipitation strengthening aur dispersion strengthening ye dono mechanism mein jo precipitates ya dispersion hote hain dispersoids hote hain wo dislocation ke saath interact karenge precipitation strengthening mein mere paas do mechanism operate hote hain mainly ek hai cutting ya shear mechanism aur dusra hai bowing mechanism ya Orowan mechanism to humne dekha ki inka interplay kis tarah se hota hai ye depend karta hai mere precipitate ke nature pe aur size ke bhi to humne yahan par do aur strengthening mechanism dekhein material mein jo strength badhate hain aage aur strengthening mechanism dekhenge ek grain size strengthening mechanism hai woh hum agle part mein padhenge abhi ke liye yahi rukta hoon dhanyavad.