Mechanical behavior of materials

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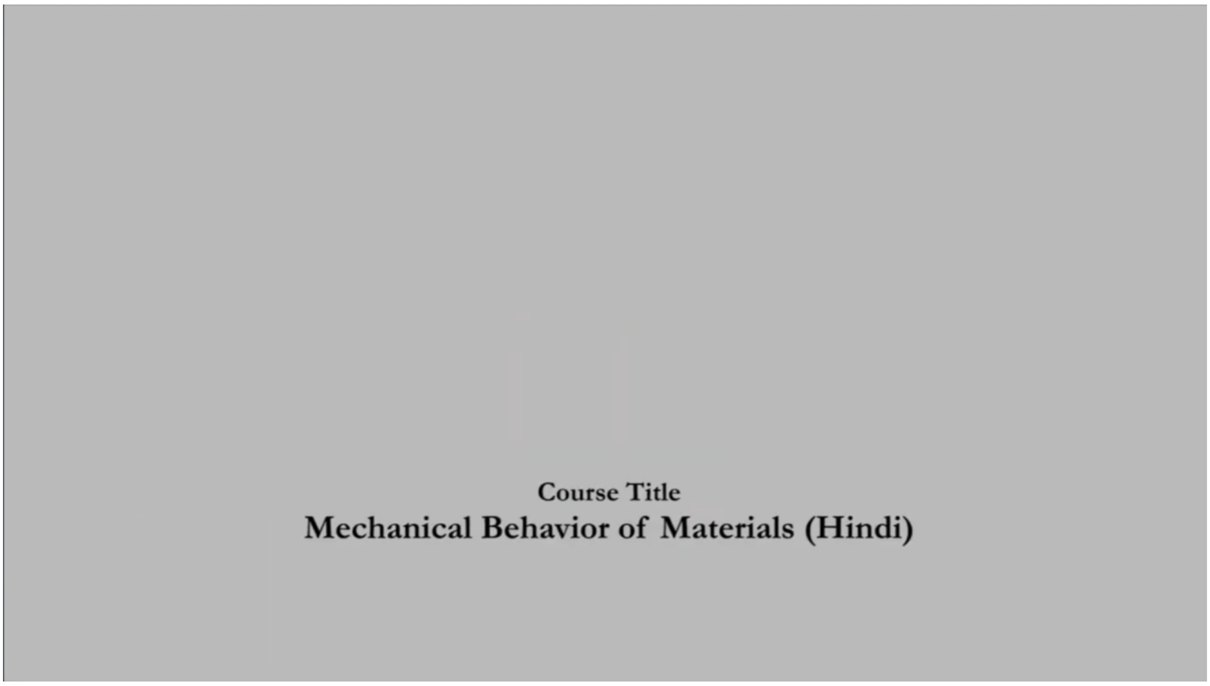
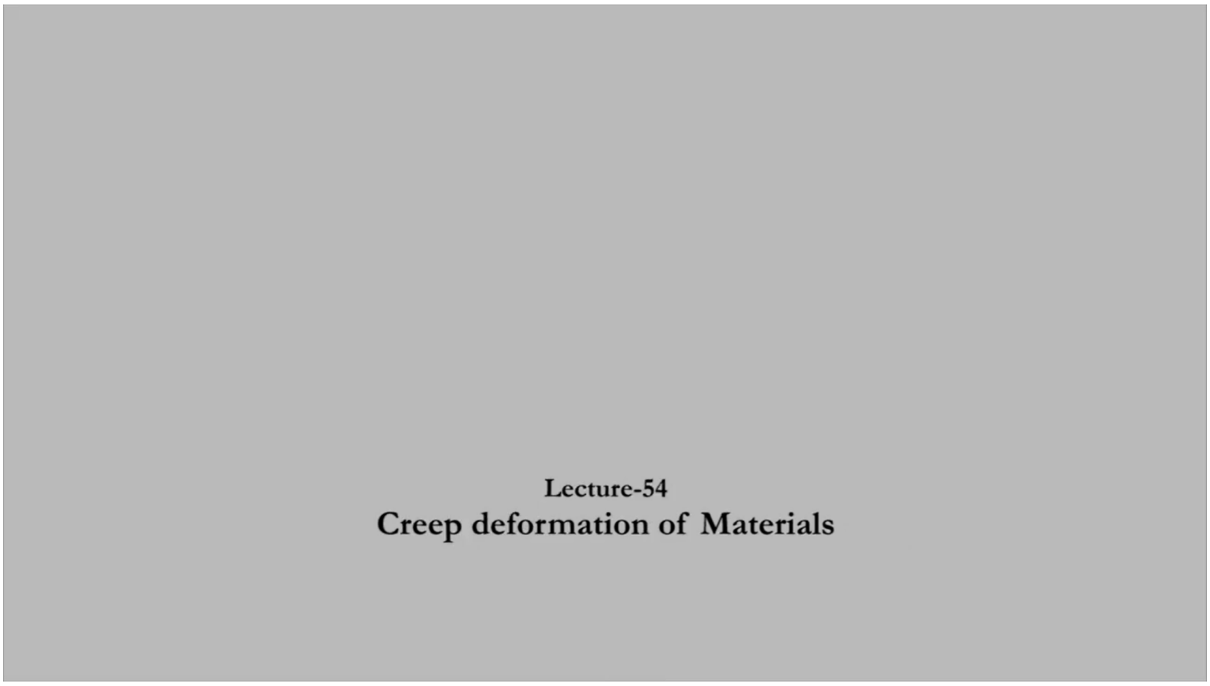
Week-10

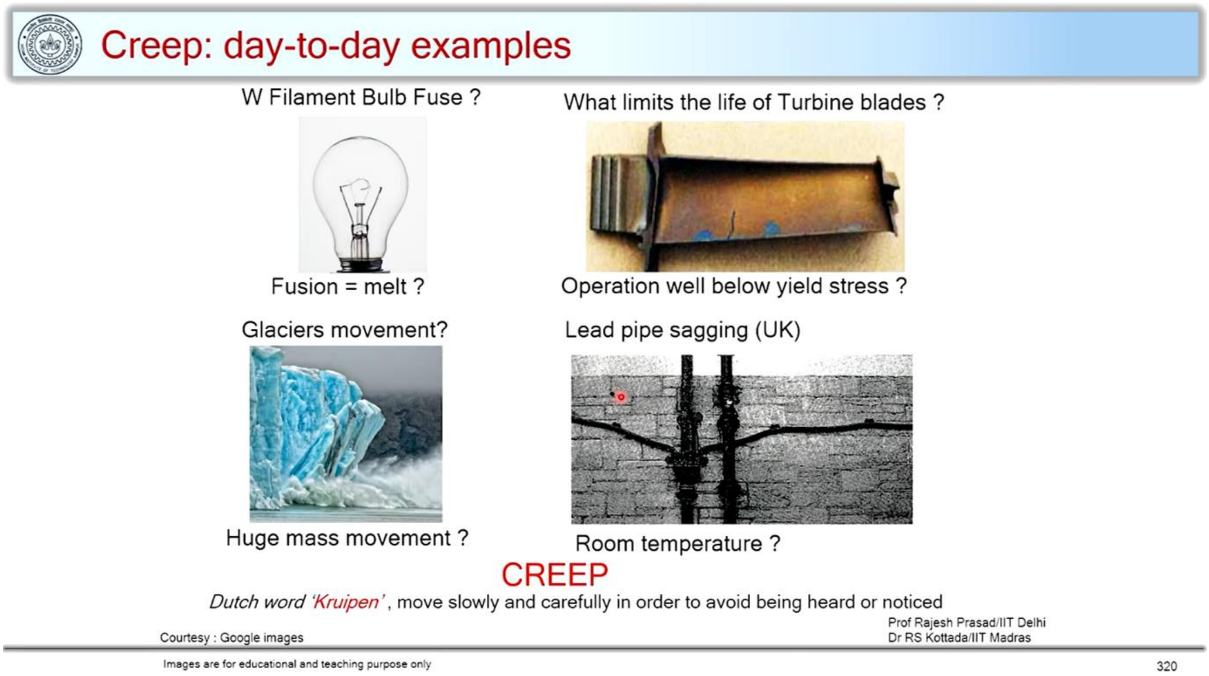
Lecture-55

Fracture & Theoretical Cohesive Strength of Materials





Namaskar, phir se swagat karta hoon aapka is course mein, Mechanical Behavior of Materials, jo ki hum Hindi mein padhenge. Last part tak humne Fracture of Materials padha. Is part mein hum ek important deformation mode dekhenge, jo ki Creep Deformation of Materials hai. To pehle creep samajhne se pehle kuch cheezein samajhte hain ki creep hota kya hai. To kuch rozmarra ki zindagi ke examples hum creep mein abhi dekhte hain, jaise ki kuch yeh bulb yahan pe maine show kiya hai. To yeh bulb lagbhag 10-15 saal pehle istemal kiye jaate the, abhi yeh bulbs dikhte nahi hain. Par is bulb ki ek khaasiyat thi ki yeh jo bulb mein ek filament tha, yeh jo filament hai yeh...



kuch high melting point elements ya metal se bana hota hai. Generally Tungsten se bana hua hota tha aur isse jab hum current pass karte the tab yeh bulb yaani yeh filament heat hota tha aur heat ke wajah se ek light produce karta tha. To iski ek life hoti thi yaani kuch samay ke baad yeh bulb hum kehte the ki fuse ho jata tha. Yaani agar fuse ka matlab agar dekhein, to iska matlab hota hai ki melt ho jana. To aur jab yeh fuse ho jata tha yaani toot jata tha tab yahan se koi current pass nahi ho payega aur bulb yaani kharab ho jayega. To is condition mein aap dekhenge ki kuch samay ke baad yeh bulb fuse ho jata tha yaani kharab ho jata tha. To yahan par hum yeh keh rahe hain ki yeh Tungsten melt ho raha hai ya kya ho raha hai...

yeh ek example tha. Doosra example hum dekhte hain ki yeh Turbine Blade yahan par show ki hai. Aur is turbine blade jab hum operate karte hain high temperature par, tab operate karte hain aur jo stress apply karte hain woh Yield Stress (σ_{γ}) ke kaafi neeche hota hai. Aur aap yahan par dekh pa rahe honge ki yeh turbine blade yahan par fail ho gaya hai kyunki yahan par iske surface par kuch cracks aa gayi hain aur yeh hum dekhte hain ki hum yield stress ke neeche bhi hain to bhi yahan par kuch deformation ho raha hai material mein aur yeh turbine blade fail ho jati hai kuch samay ke baad. Aur ek example lete hain jo ki hum nature mein hum dekh sakte hain, yaani hum dekhte hain ki Glacier Movements. Yaani yeh jo baraf ke...

chattaan hote hain inki movement hoti hai dheere-dheere. Hum dekh rahe hain ki global warming hoti hai aur aapne kuch videos bhi dekhe honge ki yeh chattaanein baraf ki chattaanein toot ke girti hain ya fisalti hain. To yahan par dekhiye yeh bahut bada mass hai jo move hota hai. To aap dekh pa rahe honge ki temperature ki wajah se, yaani hum bol rahe hain ki global warming ki wajah se, yeh chattaanon ka tootna zyada badh gaya hai, iska rate badh gaya hai, iske deformation ka rate badh gaya hai. To yeh movement jo ho raha hai woh kis phenomena se ho raha hai yeh hum dekhenge. Last ek example yahan par mein show kar raha hoon, yeh ek example hai yahan par maine kuch Lead Pipes (Pb) dikhaye hain aur yeh jo lead...

pipes the, yeh UK mein purane zamane mein paani le jaane ke liye istemal kiye jaate the. To aapko pata hai ki paani mostly room temperature par le jaya jata tha aur aap dekh pa rahe honge ki pehle kuch straight the is tarah se pipes par yeh kuch sag ho gaye yaane thoda jhuk gaye hain. To yahan par yeh jo deformation ho raha hai ek room temperature par ho raha hai to aur kuch samay ke baad ho raha hai. To yahan par hum char jo example liye yahan pe aap dekh pa rahe honge ek to material mein jo deformation ho raha hai woh kuch samay ke baad ho raha hai, woh deformation ho raha hai yield stress... mein material ko yield stress se neeche bhi rakh raha hoon yaani operating condition uska, to bhi woh deform ho raha hai. Yahan pe...

ek huge movement ho raha hai masses ka aur yahan pe aap dekh pa rahe honge is example mein yeh room temperature bhi pe bhi deform ho raha hai yeh lead pipe. To yeh jo deformation hai yeh deformation dheere-dheere ho raha hai yaani yeh unnoticed hota hai. Jaise bulbs ki baat karein to aapko pata nahi chalega hum kuch samay ke baad bulb achanak se kharab ho jayega. To ab yeh jo bulb jo kharab hone ki prakriya hai isko aap detect nahi kar paate. Similarly yeh jo hai, glacier movements yeh dheere-dheere hota hai aur achanak se humein dikhta hai ki ek chattaanein move ho rahi hain ya fisal rahi hain. Similarly yahan par bhi turbine blades mein jo deformation hai woh samay ke saath ho raha hai aur...

woh undetected jata hai. To is tarah ke deformation ko hum kehte hain Creep Deformation of material. Yaani Creep ek word hai, yeh Dutch word se aaya hai 'Kruipen' se aur jiska matlab hai ki '*move slowly and carefully in order to avoid being heard or noticed*'. Yaani jiski koi aawaz nahi hai aur noticeable nahi hai us movement ko hum creep kehte hain. To material deformation mein bhi kuch is tarah se hota hai ki samay ke saath yeh deformation accumulate hota hai aur achanak se material tootta hai ya plastically deform hota hai aur woh apne service condition mein apni service condition woh satisfy nahi kar paata. To yeh ho gaya creep deformation. Abhi creep ke baare mein aur padhte...

Plastic deformation of crystalline materials

Low temperature behaviour

$\varepsilon = f(\sigma)$

High temperature behaviour

$\varepsilon = f(\sigma, T, t)$

where; ε- strain, σ-stress,T- Temperature, t-time

What is „High Temperature"?

Material	Melting point (T_m), °C	Room temperature 25 °C
Pb	327	0.5 T_m
Al	660	0.32 T_m
Fe	1538	0.16 T_m

High temperature: $T \geq 0.4\ T_m$

Homologous temperature = T/T_m

Why high-temperature operations?

Efficiency of heat engine, $\eta = 1 - {}^{T_2}/_{T_1}$

T_1 = absoulute temperature of heat source

T_2 = absoulute temperature of heat sink

Typical in-service conditions for High-temperature components

Property	Aeroengine	Power Plant
Temperature	> 1000 °C	750 °C
Design life	10^4 h	2.5×10^5 h
σ	10 MPa	100 MPa

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hain. To creep deformation hai kya? To pehle uske pehle jaane se pehle hum dekhte hain ki Low Temperature Behavior mein kya hai. Jab hum low temperature behavior baat karenge aur High Temperature Behavior baat karte hain, to creep ek generally high temperature deformation behavior hai. Abhi mein low temperature ki jab baat kar raha hoon tab yahan pe jo plastic strain (ε_p) hai yeh sirf function of stress (σ) hai. Yaani mera jo applied stress hai uska function hai. Jitna-jitna mein stress badhaaunga utna-utna mera plastic deformation hoga, yeh hum low temperature par dekhte hain. Par high temperature mein yeh jo plastic strain hai material mein generate ho raha hai, yeh function hai mere stress (σ) ka...

mere temperature (T) ka aur time (t) ka. To high temperature behavior par aapko yeh condition hoti hai jahan par strain na ki sirf function of stress rehta hai par temperature aur time dono ka rehta hai. To jab mein high temperature ki baat karunga to ek sawal aata hai ki high temperature hai kya? To isliye ek example lete hain teen material hum lete hain: Lead (Pb), Aluminum (Al) aur Iron (Fe). Yahan pe unke melting points maine mention kiye hain. Abhi hum room temperature ki jab baat karenge (25°C) jo ki mein room temperature maan ke chal raha hoon. To agar mein yeh room temperature ko inke melting point se likhunga to kya fraction aayega? Yeh yahan pe...

maine likha hai. To yahan pe maine likha hai ki jo Lead ke liye 0.5 T_m hai. To isko kaise calculate karte hain? Yeh mera degree Celsius hai melting point, isko mein pehle Kelvin (K) mein convert karunga aur yeh jo room temperature hai isko bhi mein Kelvin mein convert karunga aur mein tab jaake inka fraction lunga aur woh jo fraction hai woh is tarah se mein yahan pe likhunga. To agar aap Aluminum ki consider karenge Aluminum ka melting point, to aap dekh pa rahe honge ki yeh jo melting point hai... isko mein Kelvin mein likhunga to lagbhag 1000 degree aa jayega aur yeh... yeh likhunga to yeh lagbhag 25 degree likhunga to yeh lagbhag 300 Kelvin aa jayega. Yeh 300 Kelvin...

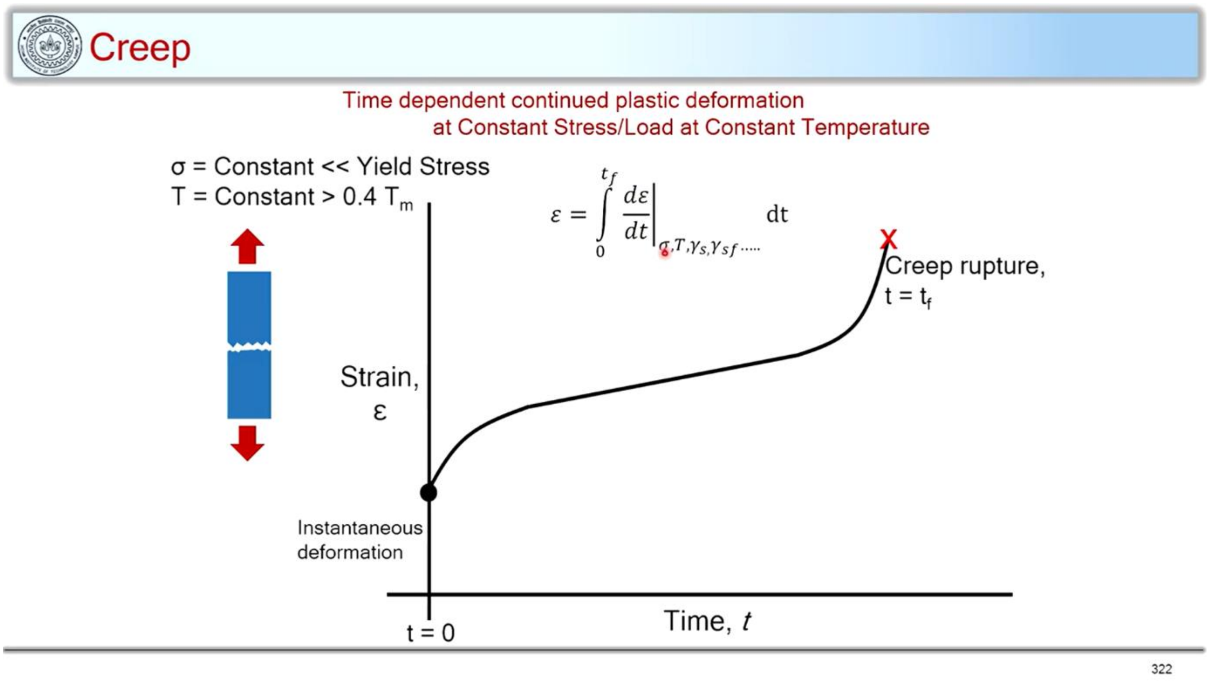
divided by 1000 Kelvin mere paas aa jayega 0.32 T_m. Is tarah se hum likhte hain. To high temperature kya hota hai? High temperature ko mein is tarah se define karta hoon melting point ke hisaab se. To aap dekh pa rahe honge ki yeh jo 25°C hai Lead ke hisaab se bahut zyada temperature hai (0.5 T_m). Aluminum ke liye sirf 0.32 T_m hai uske melting point ke hisaab se aur Iron ke liye aap dekhenge ki yeh sirf 0.16 T_m hai. To yaani yeh jo 25°C hai room temperature, Lead ke liye high temperature hai yaani zyada temperature hai (0.5 T_m) yaani aap dekh pa rahe honge uske melting point ke hisaab se zyada hai. To mein high temperature ko...

define karta hoon, koi bhi jo temperature hai jo 0.4 T_m se uske melting point se 0.4 ke fraction se agar zyada hai to woh usko mein high temperature kehta hoon. To yeh ho gaye mere high temperature ki definition. Yeh 0.4 T_m kyun hai yeh hum dekhenge jaise-jaise creep ke baare mein padhenge. To ek aur terminology yahan par mein explain karunga: Homologous Temperature. Yeh literature mein istemal hota hai jo application temperature hai divided by melting point (T/T_m). Yeh jo ratio hai isko hum kehte hain homologous temperature. Yaani agar aap... mein bolunga ki homologous temperature is application ka 0.6 hai, to aapko samajhna hai ki woh mein...

application temperature mein uske melting point se baat kar raha hoon yaani woh melting point ka 0.6 fraction hai. Yeh ho gaya mera high temperature. Abhi humein samajhna hai ki high temperature operations kyun zaroori hain? To ek simple udaharan mein dena chahta hoon yahan pe. Jab mein Heat Engine ki baat karunga to mein efficiency kuch is tarah se define karta hoon: $\eta = 1 - (T_2 / T_1)$. Aapne kuch thermodynamics classes mein padha hoga. To efficiency jo hoti hai kisi bhi heat engine ki kuch is tarah se define hoti hai aur yahan pe T_1 aur T_2 agar mein is tarah se dekhunga to T_1 yeh absolute temperature hai mere heat source ka aur T_2 mere absolute temperature hai mere heat...

sink ka. To agar mujhe efficiency agar badhaani hai to aapko dekhna hai ki yeh T_1 jo heat source ka absolute temperature hai isko mujhe badhaana padega aur T_2 ko ghataana padega. To application mein T_1 agar mein badhaaon to heat engine ki jo efficiency hai woh hamesha badhegi. To isliye humein high temperature operation hamesha-hamesha hi uski zaroorat hogi. Aur yeh jo high temperature operation humein agar zaroorat hai kyunki humein efficiency agar badhaani hai to humein high temperature material ki bhi zaroorat hogi aur high temperature material ki agar zaroorat hai to humein us high temperature par material ka deformation samajhna bhi aavashyak ho jayega. To agar mein service temperature aur high...

temperature components ki baat karunga to yahan par properties maine yahan par di hain: Temperatures, Design Life aur Stress kitna apply hai. Aur Aero Engine ki jab mein baat karunga ya Power Plant ki jab baat karunga to aap dekh pa rahe honge yahan pe temperature yeh > 1000°C hai aur yahan pe power plant mein temperature 750°C hai. To design life yahan pe aap dekh pa rahe honge... yeh stress jo hai yahan pe 10 MPa aur power plant mein aap yahan pe dekh pa rahe honge 100 MPa hai. To design life yahan pe 10^4 hours hai aur yahan pe 2.5×10^5 hours hai. To yahan pe maine do applications likhi thin aero engine aur power...



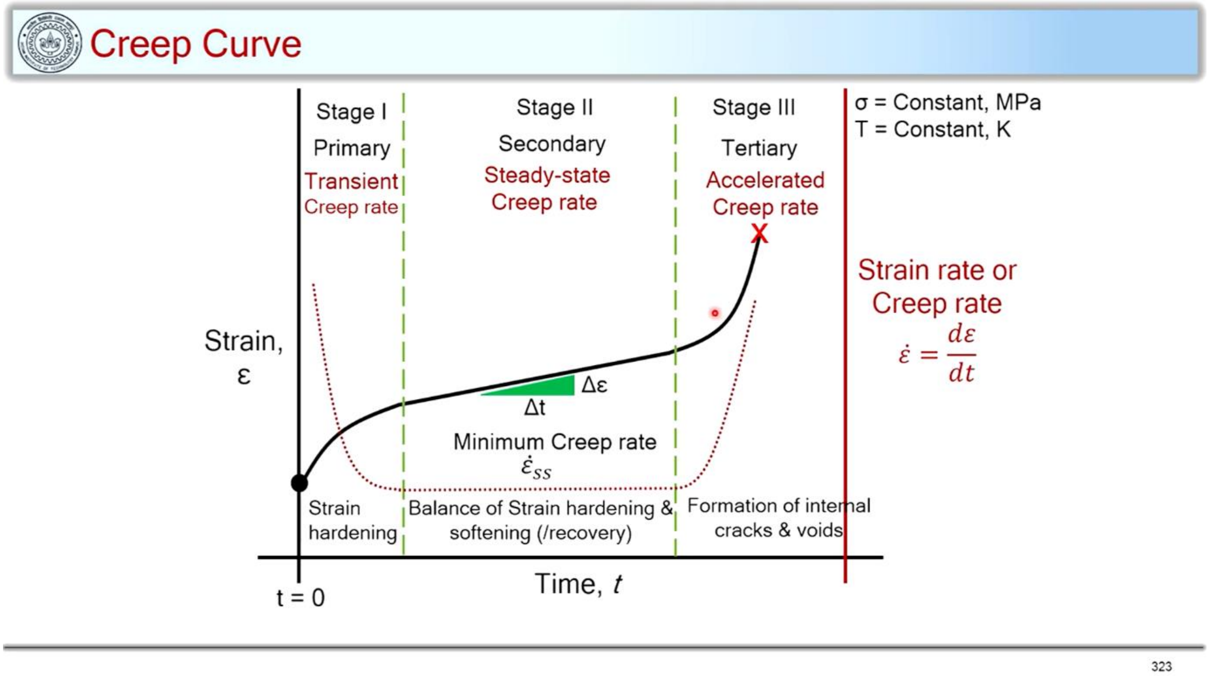
plant ki aur aap dekh pa rahe honge ki yeh jo time hai, in material ko service mein itna time zaroor bitana hi bitana hai without any failure. To humein dekhna hai ki material is long time tak sustain kare yeh saari conditions high temperatures aur stresses bhi. To yeh ho gayi high temperature material ki definition, high temperature ki definition aur high temperature operations kyun zaroorat hai iska importance. Abhi hum creep ke baare mein padhenge. Jab mein creep ke baare mein baat kar raha hoon tab mein generally high temperature ki hi baat kar raha hoon kyunki creep high temperature deformation mein hi aata hai. Creep ko mein agar define karunga kuch is tarah se mein define kar sakta hoon: Creep ek Time-Dependent Continued Plastic Deformation hai.

Yaani hum plastic deformation ki jab baat karenge, yaani agar yeh deform ho gaya to mein yeh material woh strain ko recover nahi kar payega. Yaani permanent deformation mera material ka ho raha hai aur yeh deformation permanent hai yaani yeh deformation time dependent hai yaani time ke saath yeh deformation badh raha hai. Aur yeh kab badh raha hai? At Constant Stress (σ) or Load at Constant Temperature (T). Generally mein temperature constant rakhta hoon aur stress aur load bhi constant rakhta hoon aur time ke saath jo plastic deformation ho raha hai isko mein creep kehta hoon. To maan lete hain ki mein stress constant rakh raha hoon jo ki yield stress (σ_Y) se neeche hai...

aur yeh jo temperature hai woh thoda zyada hai yaani high temperature hai jisko humne define kiya tha 0.4 T_m se zyada hai. Abhi dekhte hain ki kuch mera material aisa hai aur yahan pe mein ek tensile stress isko apply kar raha hoon aur mein jab deformation ki baat karunga time ke saath, to mein strain (ε) Y-axis par plot kar raha hoon aur time (t) X-axis pe plot kar raha hoon. To jaise-jaise time badhega waise-waise mein dekhna chahta hoon ki mera deformation kis tarah se badh raha hai. To hamara strain jo hai, plastic strain is tarah se maine Y-axis par rakha hai. Jab mein yeh conditions apply karta hoon aur time ke saath agar deformation dekhna chahta hoon to...

material kuch is tarah se deform hota hai. Aap dekh pa rahe honge ki yeh material yahan pe deform ho gaya aur yahan par mujhe kuch is tarah se deformation milta hai jo ki is curve ko kehte hain Creep Curve. Aur material yahan par kuch samay ke baad fail ho jayega. To yahan par mein ek aur parameter define karna chahta hoon yeh jo hai yahan par aap dekh pa rahe honge time shoony (zero) jab tha isko mein Instantaneous Deformation kehta hoon ki jaise maine load apply kiya ek zero samay pe wahan par kuch plastic strain develop hua hai material pe. Aur jaise-jaise time badh raha hai, mein to load aur temperature constant rakh raha hoon, to time ke saath deformation kuch is tarah se badh raha hai. To yahan par aap dekh pa rahe honge t = t_f...

pe yeh material fracture ho gaya. Isko mein kehta hoon Creep Rupture. Abhi yeh jo plastic strain hai agar mujhe total plastic strain kitna deform hua hai isko agar calculate karna hai to mein kuch is tarah se calculate kar paunga. Yeh mera strain hai, total strain (creep strain) keh sakta hoon mein ise. Yeh mein calculate kar raha hoon ki kitna small change in strain with respect to time aur baaki ke jo parameters hain maine sab constant rakhe (σ, T, surface energy, stacking fault energy) yeh saare parameters jo material ke parameters hain constant hain aur mein calculate kar raha hoon ki yeh mera plastic strain kis tarah se...



change ho raha hai time ke saath aur mein total time ke saath agar mein integrate karunga yaani yahan se shoony se t_f tak, to mujhe ek total plastic strain yahan pe mil jayega. Mathematically kuch is tarah se maine plastic strain ya creep strain ko define kiya hai. To yahan pe aap dekh pa rahe honge yeh jo term hai isko mein kehte hoon Creep Strain Rate (dε/dt). Kuch is tarah se meri condition hai: stress constant hai, temperature bhi constant hai jo ki 0.4 T_m se zyada hai aur mujhe kuch is tarah se creep curve mil raha hai. To agar mein is creep curve ko dekhunga at time t = 0, yeh mujhe instantaneous deformation mil raha hai, yahan pe mera material fail ho raha...

hai. Aur agar mein is creep curve ko is tarah se dekhunga to mein agar is curve ka nature dekhunga to mein teen region mein isko divide kar sakta hoon. Aap dekh pa rahe honge ki yahan pe strain is tarah se badh raha hai aur yahan pe lagbhag strain jo change ho raha hai time ke saath woh linear hai aur yahan se jo strain badh raha hai woh accelerated way se badh raha hai yaani bahut tezi se badh raha hai. To mein teen region is tarah se mark kar sakta hoon is creep curve ko jab mein observe karta hoon to. To yahan pe yeh jo stages hain yaani yeh teen region hain isko mein teen naam de sakta hoon material failures ke yaani plastic strain kis tarah se Stage 1, Stage 2 aur Stage 3... yaani...

beginning se end tak mein is tarah se isko divide kar raha hoon. Isko mein aur kuch naam de sakta hoon jaise Primary kyunki yeh initial mein chalu hua hai isliye mein Primary kehta hoon. Isko mein kahunga Secondary aur isko mein kehta hoon Tertiary. To yeh sequence wise mere stages is tarah se badh rahe hain. Abhi humne last slide mein baat ki thi ki agar mein strain ki baat kar raha hoon time ke saath to mein strain rate ($\dot{\varepsilon}$) bhi plot kar sakta hoon. To mein maan leta hoon ki mein strain rate is tarah se plot karunga dε/dt vs time. Aur strain rate agar mein isko strain rate nikaalne ki koshish karunga to mujhe strain pata hai aur...

time pata hai to mein agar iska derivative lunga is curve ka to mujhe strain rate milega kisi particular time pe. To woh jo strain rate hai kuch is tarah se vary hota hai. Agar mein iska derivative lunga to mujhe kuch is tarah se milta hai aur ise U-curve kehte hain kyunki generally iska nature jo hota hai woh 'U' ki tarah dikhta hai. To aap dekh pa rahe honge yahan par jo strain rate hai, strain rate high strain rate tha aur woh decrease ho raha hai, change ho raha hai aur ek low value yaani minimum value par aa raha hai kuch is samay pe. Yaani mere Primary pe high strain rate tha aur woh decrease ho raha hai aur ek constant value yahan par mujhe mil rahi hai is tarah se...

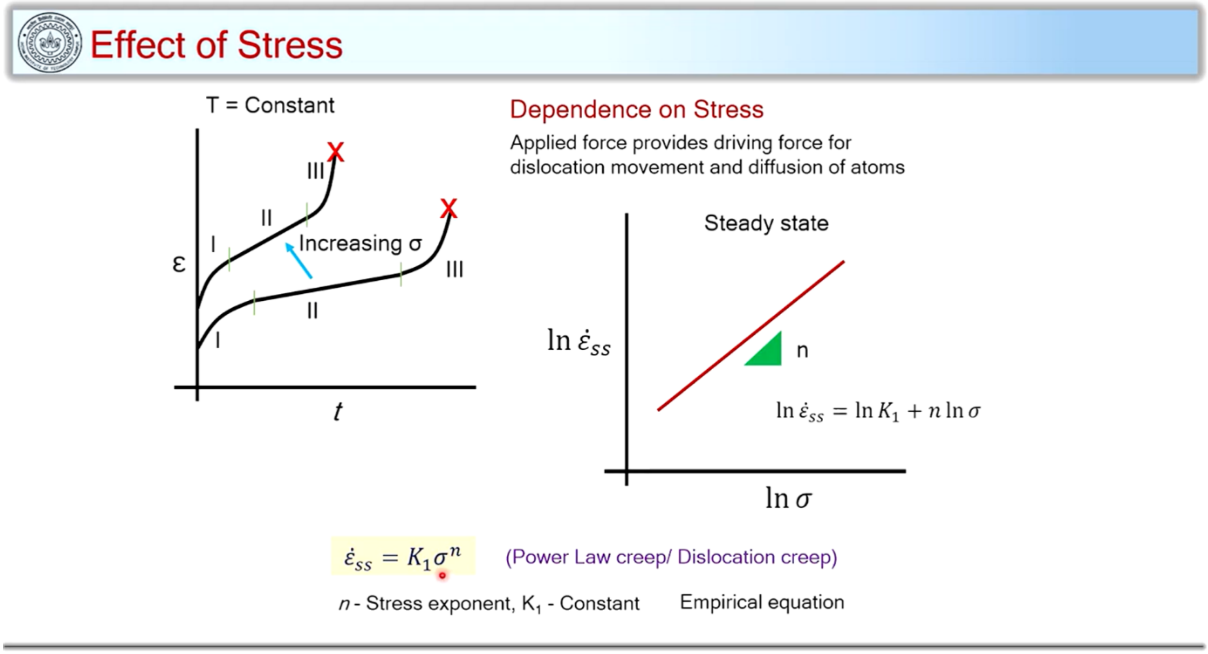
aur jaise Tertiary mein jab baat karunga tab mein mere jo strain rate hai kuch is tarah se increase ho raha hai. To yeh jo strain rate ki values hain iske upar bhi creep stages ke naam likhe gaye hain. To pehla agar mein naam dekhunga to isko mein kehta hoon Transient Creep Rate. Yaani Primary ko hi mein transient creep rate ki tarah kahunga kyunki yahan par aap dekh pa rahe honge ki creep rate change ho raha hai ya transient ho raha hai. To transient nature hai yahan strain rate ka. Yahan par mujhe jo strain rate milra hai woh constant hai isko isliye mein kehta hoon Steady State Creep Rate ($\dot{\varepsilon}_{ss}$). Yahan pe change nahi ho raha hai mostly...

creep rate yahan pe steady state hai aur yahan pe creep rate change ho raha hai par yahan pe yeh jo badh raha hai creep rate is tarah se isliye isko kehte hain Accelerated Creep Rate. Aur aap jaise hi Tertiary mein aayenge strain rate is tarah se badhega aur material yahan par is time ke baad fail ho jayega. Abhi yeh jo nature abhi mila hai woh kyun mila hai yeh bhi hum dekhenge. Pehle engineering applications ke liye hum baat karenge tab yeh jo value hai yahan pe steady state creep rate mein agar mein iska slope lunga yeh mujhe milega minimum creep rate value ya steady state creep rate value. Yeh application mein zyada istemal kiya jata hai yaani creep jab hum study karte hain to...

yeh jo value hai minimum creep rate ya steady state creep rate iska bahut importance hai kyunki mera jo material hai sabse zyada steady state mein rehta hai isi isi steady state mein rehta hai application ke dauran. To isliye minimum creep rate aur ya steady state creep rate bahut importance rakhta hai jab mein engineering applications ki baat karta hoon. Abhi aaiye jaante hain ki yeh jo nature mujhe strain rate ka is tarah se mil raha hai yeh kyun mil raha hai? To yeh isliye mil raha hai jaise humne dekha hai ki yahan pe strain badh raha hai aur jaise-jaise strain badhta hai material mein waise-waise wahan par Strain Hardening ki sambhavna bhi badhti hai. To yahan par...

material mein strain hardening ho raha hai aur do mechanism yahan par play karte hain: ek Strain Hardening aur Softening Mechanism. To yahan pe strain hardening mechanism mera dominate kar raha hai isliye yahan pe creep rate decrease ho raha hai is region mein aake. Mere paas do mechanism ka balance ho jayega ya yahan par aap dekh pa rahe honge strain rate ya creep rate constant hai ya steady state hai. Yahan par yeh jo do hardening mechanism hain (strain hardening mechanism ya softening mechanism), softening mechanism kis tarah se hote hain? So softening mechanism mere Recovery, Recrystallization, Grain Growth yeh mere softening mechanism mein aate hain. To...

microstructure mein yahan par changes ho rahe hain aur yeh uske wajah se strain hardening aur strain softening mujhe milta hai ya softening mechanism milte hain aur unka balance mujhe is region mein milta hai ya steady state creep rate ke dauran mujhe milta hai. Aur yahan par aap dekh pa rahe honge ki mujhe accelerated creep rate milta hai. To yahan par jaise-jaise hum time ke saath material mein deformation accumulate ho raha hai waise-waise wahan pe defects accumulation badh jata hai jis tarah se voids ya internal cracks ya vacancies accumulation ho jata hai. Uske wajah se yeh defects badh jaate hain aur uske wajah se material ki jo stress bearing ability hai woh decrease...



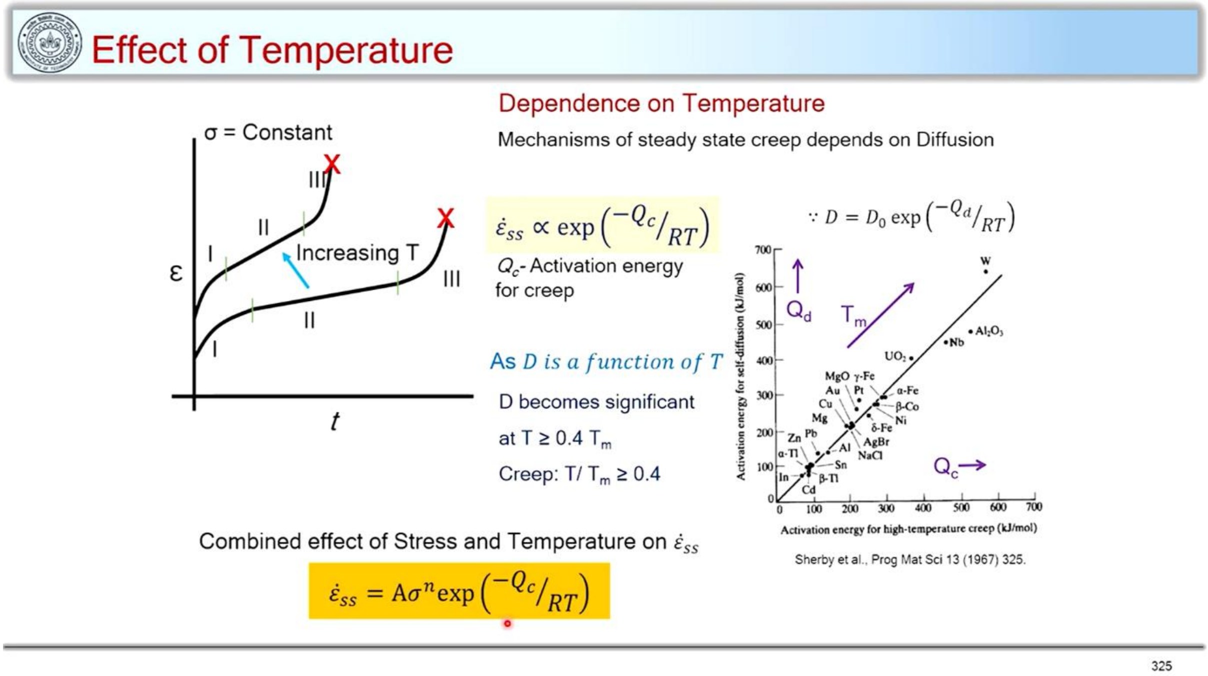
hoti hai aur yahan pe material fail ho jata hai. To yahan pe mein dekh pa raha hoon ki jo strain rate ka jo contribution hai woh majorly aa raha hai kyunki mera material jo stress (kyunki constant stress par baat kar raha hoon) woh handle nahi kar pa raha hai kyunki yeh defects ka dominance badh gaya hai microstructure mein. To yeh ho gaya mera creep curve aur yeh creep nature is tarah se hota hai, typical creep curve. Yaani most of the material (metallic material ya alloys) is tarah se creep curve dikhate hain. To yeh ho gaya simple introduction mere creep curve ka. Abhi hum dekhte hain ki jab mein stress ki baat karunga to humne bataya tha ki creep mein hum stress ko constant rakhte hain. To yahan par...

dekhte hain ki agar mein stress change karta hoon. To stress change jab karunga tab mein temperature ko constant rakhunga aur dekhunga ki yeh jo strain change ho raha hai time ke saath kis tarah se ho raha hai. To mera ek creep curve hai aur yeh ek stress pe hai aur mein stress agar increase karta hoon to yeh creep curve kuch is tarah se mujhe milega ek particular temperature pe aur jab stress high hai is tarah se to aap dekh pa rahe honge ki yeh jo low stress hai aur yeh high stress hai is pe material jaldi fail ho gaya hai. Aap dekh pa rahe honge ki time yahan pe kam ho gaya yaani material jaldi fail ho gaya high stress pe aur yeh jo regions hain jo humne mark kiye the Stage 1, Stage 2 aur Stage...

3, yeh bhi yahan pe shift ho gaye. Yeh shift ho gaye low values of time pe yaani jaldi occur ho rahe hain yaani Stage 1 bhi jaldi aa raha hai, Stage 2 bhi aur yeh jo region hai yaani yeh curve hai yeh thoda shrink ho gaya yaani jaldi failure ho raha hai yahan par. To is tarah se humein change milta hai stress ke saath. Jaise mein stress badhaaunga waise-waise mere yeh region bhi shrink ho rahe hain aur material bhi jaldi fail ho raha hai. To aap dekh pa rahe honge ki jab mein dependence of stress ki baat karunga tab yeh kyun ho raha hai? Kyunki yeh jo stress jo maine increase kiya hai woh kya karega? Woh ek driving force provide karega mere Dislocation Motions ko aur Diffusion of Atoms ko.

Humne dekha ki creep high temperature ek phenomena hai aur jab mein stress increase karunga to dislocation ki movements bhi badhengi aur diffusion of atoms bhi badhega, woh enhance hoga iske wajah se material jaldi fail hoga jaise mein stress padhaaunga. Agar mein strain rate ki baat karunga, jaise mein steady state strain rate ki baat karunga aur jaise mein stress ke saath isko plot karne ki koshish karunga (yahan par maine log-log plot kiya hai). Jab mein agar yeh relation dekhta hoon most of the materials ke liye to mujhe ek steady state region mein kuch is tarah se linear relation milta hai. Yaani strain rate ka relation milta hai stress ke saath steady state creep rate mein. Agar...

yahan par maine steady state creep rate nikaala (yaane slope nikaala) aur yeh plot kiya stress ke saath kis tarah se change ho raha hai, to mujhe kuch linear relation milega aur is linear relation ko mein kuch is tarah se likh paunga yaani ek simple equation (linear equation) likhunga aur yahan par yeh jo slope hai yeh mera Stress Exponent (n) hai. Agar mein isko as a power law express karunga to mein kuch is tarah se likh paunga is equation ko. Mein mathematically is tarah se rearrange karke likh sakta hoon: yaani steady state creep rate $\dot{\varepsilon}_{ss} = k_1 \sigma^n$. Yeh k_1 ek constant hai aur 'n' yeh mera stress exponent hai. Yeh jo relation hai isko kehte hain Power Law Creep or Dislocation Creep aur yeh empirical relation...



ya empirical equation hai. Iska matlab yeh hai ki iska yeh experiments ke dwara observe kiya gaya hai iske peeche jo physics hai woh well-defined nahi hai. Isko Power Law Creep kehte hain creep ke literature mein. To yeh ek relation humein useful relation humein mil gaya strain rate ka stress ke saath. To hum dekh sakte hain ki jaise-jaise mein stress badhaaunga waise-waise mera strain rate badhega. Abhi hum dekhte Effect of Temperature. Humne baat ki thi jab mein effect of temperature dekhunga to mein stress constant rakhunga. Yahan par maine stress constant rakha hai aur yeh jo generally stress jo hota hai woh yield stress ke neeche hota hai yeh humne dekha. Abhi hum kya karenge... yeh...

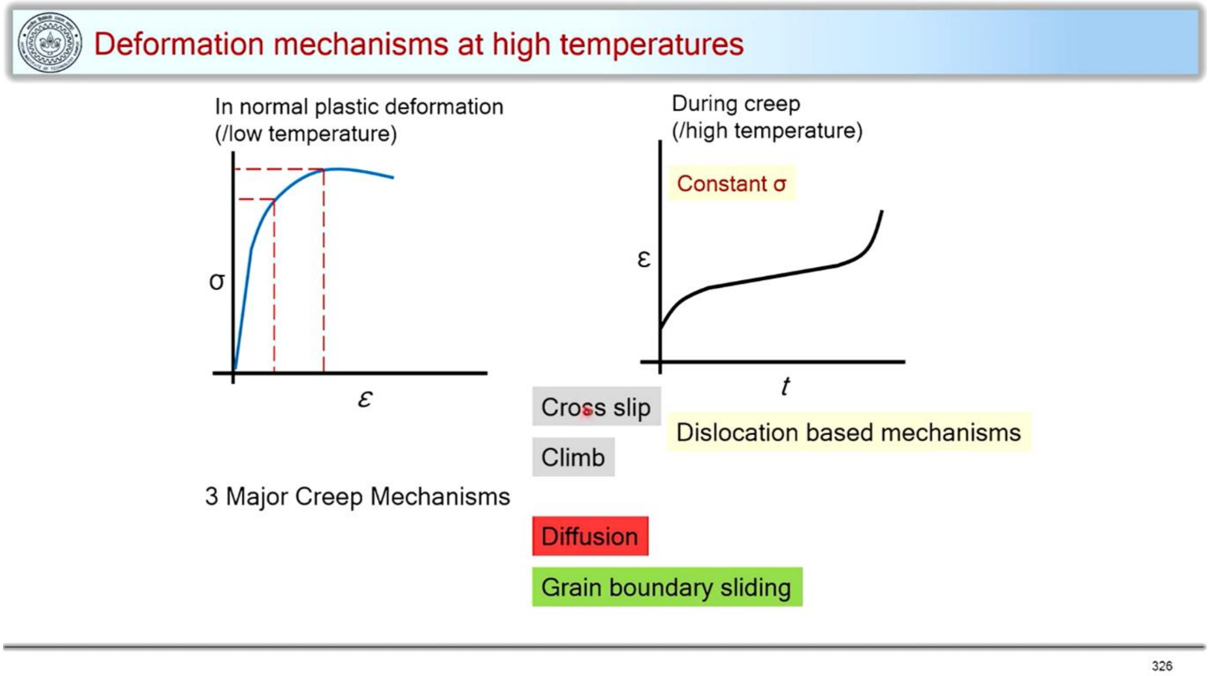
mujhe plastic strain yahan pe mein plot karunga temperature ke saath kis tarah se change ho raha hai. To yeh typical creep curve mujhe milta hai ek particular temperature pe mujhe milega aur yahan par mein agar temperature increase karunga to mujhe similar change milega jo mujhe stress ke saath mila era yaani material agar high temperature par mein deform karne ki koshish karunga to material jaldi fail ho jayega aur yeh jo stages bhi hain creep ke stages woh shift ho jayengi ya shrink ho jayengi kuch is tarah se (Stage 1, Stage 2, Stage 3). Abhi hum dekhte hain ki is temperature ka effect kyun ho raha hai creep rate pe ya creep rate kyun badh raha hai jaise-jaise mein temperature badhaata...

hoon. To temperature jaise-jaise badhaata hoon waise-waise mera diffusion material mein badhta hai. Yaani mein agar steady state creep rate ki hi baat karunga yaani is Stage 2 ki baat karunga, ismein agar mein slope nikaal ke steady state creep rate iska mein plot karunga temperature ke saath to mein kuch ek relation nikaal sakta hoon aur woh relation depend karega mere diffusion of material. To mein steady state creep rate ko kuch is tarah se likh sakta hoon: $\dot{\varepsilon}_{ss} \propto \exp(-Q_{\square} / RT)$, jahan par $Q_{\square}$ jo hai woh Activation Energy for Creep hai. Yeh isliye likh sakte hain kyunki mujhe yeh relation pata hai $D = D_0 \exp(-Q^d / RT)$.

Yeh aapne dekha hoga diffusion ka equation. To hum dekh sakte hain ki jaise-jaise temperature badhta hai waise-waise yeh diffusivity badhti hai aur yeh relation Sherby ne dikhaya tha ki aap dekh pa rahe honge ki jaise yahan pe activation energy for self-diffusion yeh plot hai Q^d aur yahan pe activation energy for creep deformation (creep ke liye) is tarah se plot hai. To aap dekh pa rahe honge ki yeh jo relation hai in dono ke beech mein linear relation hai. To yahan par jaise-jaise melting point badh raha hai mere material ka waise-waise jo creep energy hai ya diffusion self-diffusion energy hai woh bhi badhegi aur creep ke liye jo bhi apparent activation energy...

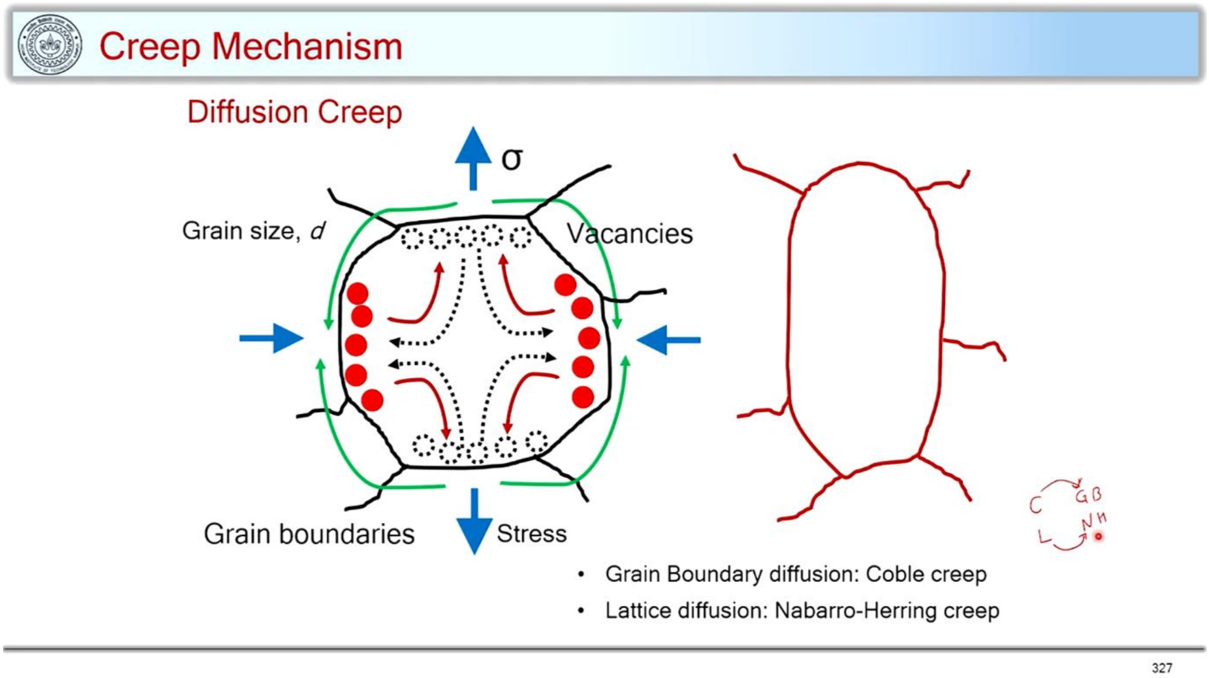
lagegi woh bhi badh rahi hai aur inmein ek linear relation humne dekha hai $Q_{\square}$ aur Q^d mein. Aur yeh nature humein pata hai exponential nature $\exp(-Q^d / RT)$ isliye hum strain rate ko bhi is tarah se likh sakte hain. Abhi hum dekhte hain ki jab hum D ki baat karte hain, D ka jo function hai yeh agar diffusivity ki baat karenge temperature ke saath kuch is tarah se hum dekh pa rahe honge ki jaise-jaise temperature badhta hai aur ya temperature $\geq 0.4\ T_m$ hota hai (ya homologous temperature ki baat karenge ≥ 0.4 hota hai) tab yeh jo diffusion hota hai woh significantly badh jata hai. Isliye hum creep jab dekhte hain, creep material creep deformation...

dekhte hain woh $0.4\ T_m$ ke baad significant ho jata hai kyunki material mein jo diffusion hai woh significantly badh jata hai above $0.4\ T_m$. To isliye creep jab hum consider karte hain to is temperature ke baad creep deformation kaafi badh jata hai is temperature ke baad. To mein ek simple relation yahan par likh sakta hoon jab mein stress aur temperature ko combine kar raha hoon. To yahan par aap dekh pa rahe honge ki maine steady state creep rate ko is tarah se likha: $\dot{\varepsilon}_{ss} = A\,\sigma^n \exp(-Q_{\square} / RT)$. To yeh dono humne combine kar liye. Yeh ek simple approach hum yahan par istemal kar rahe hain, yeh ek empirical relations hi hain jo humein practically observed phenomena se humne...



likhe hain. Jab abhi mein Deformation Mechanisms dekhunga at high temperature. To abhi dekhte hain ki creep mein kya-kya deformation mechanisms ho sakte hain. To pehle dekhte hain ki low temperature pe kya deformation mechanism hai. To hamare paas stress-strain curve hai is tarah se aur yeh low temperature pe hum baat kar rahe hain tab hum dekhte hain ki agar mujhe yeh strain chahiye material mein plastic strain to mujhe itna stress apply karna hai aur agar mujhe strain badhaana hai material mein yaane mujhe itna deformation chahiye to mujhe uske corresponding zyada stress apply karna hoga. Par humne dekha ki creep mein mein ek to constant stress...

rakhta hoon ya constant temperature rakhta hoon aur plastic strain yahan pe time ke saath change ho raha hai kuch is tarah se humne dekha hai creep curve mein. To yeh jo phenomena hai yaani plastic strain jo develop ho raha hai time ke saath woh kuch mechanism se develop ho raha hai yaani kuch micro-mechanisms hain jo microstructure ke saath related hain. To first mechanism yahan pe hum dekhenge ki kuch Diffusion Based Mechanism hai, kuch Dislocation Based Mechanism hai jaise Cross Slip aur Climb. Aur yahan par dekhenge ki ek jo mechanism hai Grain Boundary Sliding, yeh dono ka combination hoke ek effect deta hai. To hum dekh pa rahe hain ki...



yeh jo major mechanism hain mere, yeh time ke saath operate hote hain aur yeh plastic strain develop karte hain material mein. To aaiye jaante hain ki mechanism kya-kya hain. To sabse pehle dekhte hain Creep Mechanism jismein hum Diffusion Creep ki baat kar rahe hain. To jab mein diffusion creep ki baat kar raha hoon tab mein mere paas agar polycrystalline material hai aur mein agar kuch grain is tarah se mark kar raha hoon yahan par yeh grain boundaries maine mark ki hain aur humne dekha hai ki kuch stress hum apply karte hain is ek grain size maan lete hain grain size 'd' hai mera aur kuch stress apply karte hain 'σ'. Yeh constant stress hai, generally yeh yield...

stress se neeche hota hai. Par yeh jab stress hum apply karte hain tab aap dekh pa rahe honge ki yeh jo kuch grain boundaries hain yaani hum sample pe apply karte hain par kuch grains is tarah se align honge ki kuch grain boundaries yahan pe perpendicular rahegi mere applied stress pe aur kuch grain boundaries yahan par kuch is tarah se yeh rahegi parallel mere applied stress se. Abhi aap dekhenge ki yeh jo maine stress apply kiya hai iske wajah se kya hoga material mein? Yaani yahan par aap dekh pa rahe honge ki yeh jo tensile stress agar grain boundary mein lag rahi hai (yeh grain boundaries pe) to yeh... yeh jo boundaries hain is par compressive stress nahi lagega yeh humne dekha tha ki...

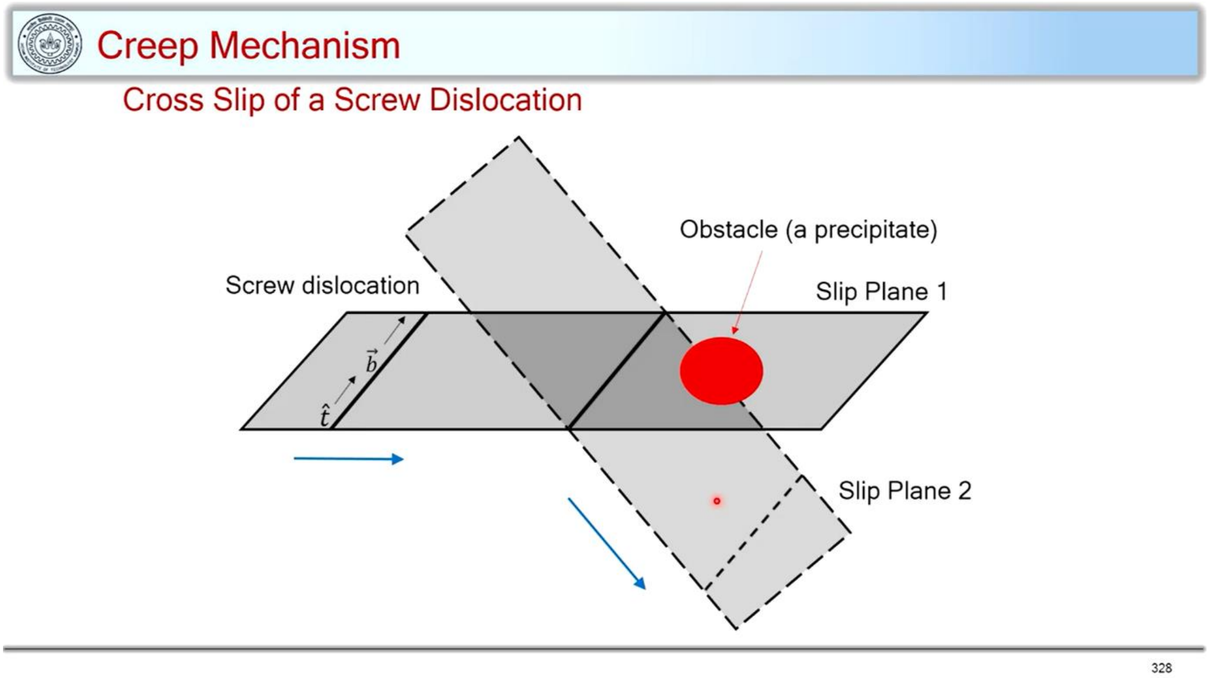
yeh Poisson's nature hai. Theek hai? To yahan pe yeh jo boundaries hain yeh compressive stresses experience karengi, yeh jo boundaries hain yeh tensile stresses experience karengi. Iske wajah se kya hoga jo boundaries jahan pe tensile stress experience ho raha hai wahan pe vacancy concentration badh jayega. Humne dekha tha jab hum climb ki baat kar rahe the material mein ya thermal equilibrium concentration of vacancies ki baat kar rahe the tab humne dekha tha agar stress mein apply karta hoon to wahan pe vacancy formation badh sakta hai ghat sakta hai depending on nature of stress. To agar tensile stress hai to vacancy concentration badhega aur compressive stress hai to wahan par vacancy concentration...

ghatega. To yahan par maine dikhaya ki jo boundary jahan pe tensile stresses lag rahi hain is do boundaries par yahan pe vacancy concentration badh jayega aur mein yahan par keh sakta hoon ki yahan pe vacancy concentration us tarah se hai nahi to yahan par ek differential vacancy concentration ho jayega grain ke andar hi aur uske wajah se kya hoga mera diffusion hoga. Aur diffusion kis tarah se hoga? Jaise yeh vacancies hain kuch is tarah se diffuse hongi is boundaries ke taraf jahan pe compressive stresses hain aur yeh jo mass flow hai kuch is tarah se hoga is boundaries ke taraf jahan pe tensile stress lag raha hai. To yaani compressive nature se tensile jo nature hai boundaries ki taraf...

wahan pe mass flow hoga. To is mass flow ke wajah se material mein plastic deformation hoga yeh mera Diffusion Creep hai. To aap dekh pa rahe honge ki yahan par maine kuch arrows is tarah se mark kiye yaani yeh lattice ke andar se diffusion ho raha hai mere. To doosra path is tarah se bhi ho sakta hai ki yeh jo diffusion hai vacancies ka woh grain boundaries ke through bhi ho sakta hai. To yeh jo do paths maine yahan par mark kiye (lattice ke andar aur grain boundaries se diffusion) iske wajah se mere paas do creep mechanism hote hain diffusion creep mechanism aur... aur yeh jo do diffusion creep mechanism...

hain uske wajah se mere grain ka shape change hoga aur grain is tarah se elongate hoga jis direction mein mera stress lag raha hai. To aap dekh pa rahe honge grain ki... grain is tarah se deform ho gaya hai. To yeh mere plastic deformation ka kaaran ban jaati hai. Abhi hum dekhenge ki maine do paths yahan par mention kiye: jo grain boundary diffusion (yaani agar yeh vacancy grain boundary ke through move ho rahi hai is tarah se) to inko mein kehta hoon Coble Creep. Agar woh lattice ke through agar move ho rahi hain kuch is tarah se, isko mein kehta hoon Nabarro-Herring Creep. To yeh do meri creep mechanism yahan pe ho gayi aur yeh jo creep mechanism hain woh temperature dependent hain. Agar mein high temperature...

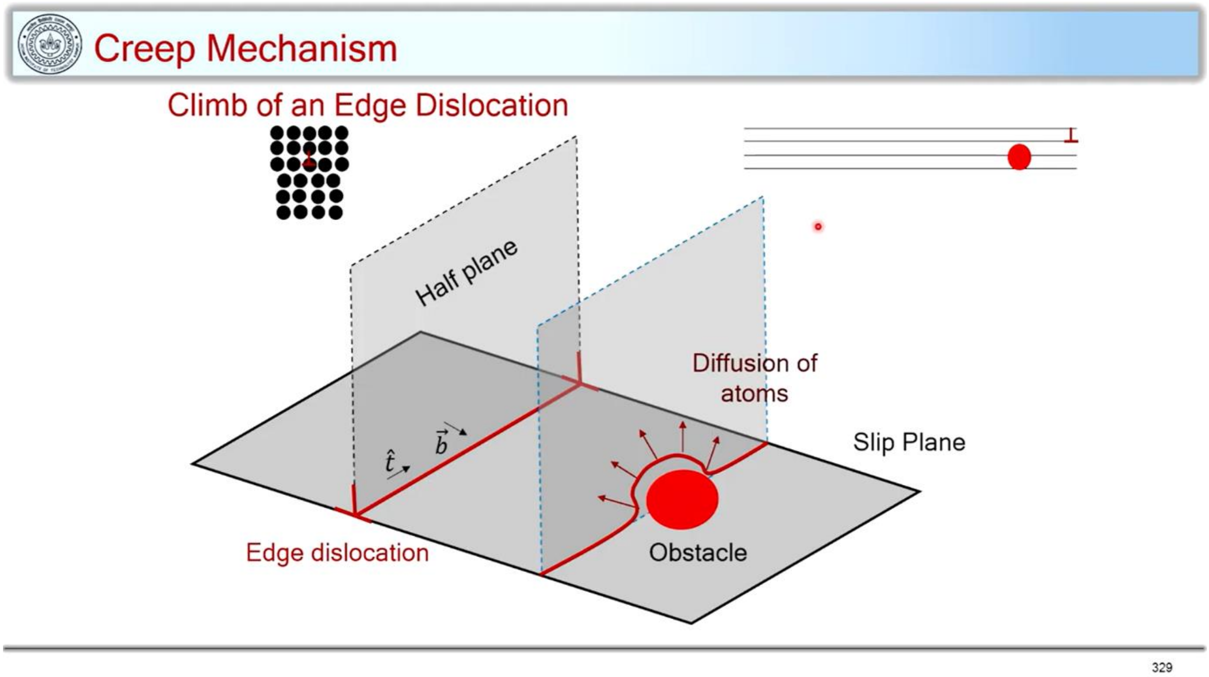
par baat karunga to mujhe lattice diffusion milta hai (Nabarro-Herring). Agar low temperature par mein baat karunga to mujhe grain boundary diffusion milta hai (Coble). Yeh dono mechanism baad mein dekhenge ki kis tarah se temperature ke saath aur stress ke saath affected hote hain. To yeh ho gaya mera introduction creep mechanism ka jab mein diffusion creep ki baat kar raha hoon. To generally ek difficulty hoti hai ki grain boundary diffusion aur lattice diffusion ko kis tarah se hum samajh sakte hain. To mein is tarah se yaad rakhta hoon hamesha ki jaise Coble ki jab mein baat karunga aur grain boundary ki baat karunga to 'C' mera 'G' ke paas hai close hai alphabetic order mein. Aur lattice diffusion ki jab mein baat karunga...



to Nabarro-Herring... to 'L' jo hai woh 'N' ke paas hai. To mein kuch is tarah se yaad rakhta hoon ki jab mein Coble ki baat karunga to grain boundary diffusion hai aur jab lattice ki baat karunga tab Nabarro-Herring creep ho raha hai. Abhi hum dekhte hain ki kuch Dislocation Based Mechanism. Yeh kuch mechanism humne padhe the ki Cross Slip ho sakta hai ek dislocation ka. To agar mere paas kuch is tarah se slip plane hai aur mere paas kuch is tarah se screw dislocation hai aur screw dislocation ki baat karunga to tangent vector parallel rehta hai Burgers vector se. Aur ek obstacle hai yahan pe (precipitate) is slip plane pe. To jab...

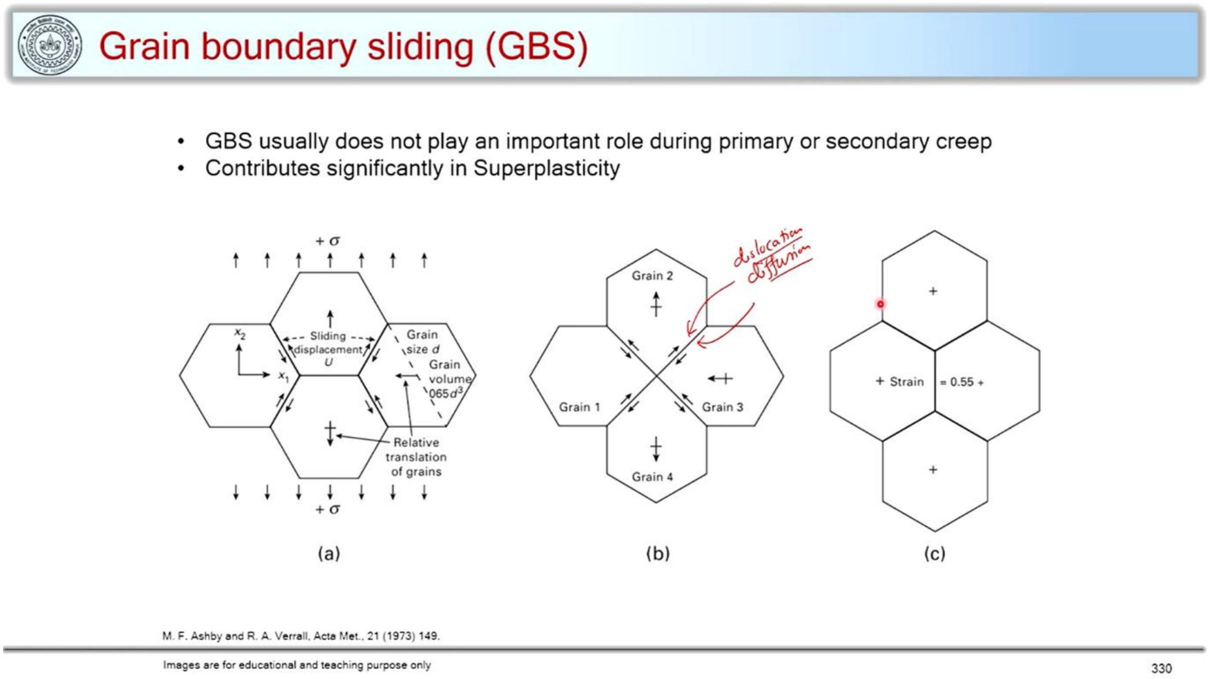
mein stress apply karunga (constant stress hai aur high temperature par), to yeh dislocation move hoga aur is obstacle se aage aake ruk jayega. To kuch is tarah se aake ruk jayega. To humein pata hai ki yeh jo screw hai yeh doosre slip plane pe bhi move ho sakta hai jahan par kyunki iske paas tangent vector aur Burgers vector parallel hai. To is slip plane pe is tarah se move ho sakta hai. Kyun move ho sakta hai? Kyunki yahan par ek obstacle hai jo allow nahi karega mere dislocation ko is plane pe move hone ke liye. Aur hamara paas sufficient high temperature aur time ke saath yeh screw dislocation is tarah se cross slip ho jayega stress ke influence ke andar. To yeh ho gaya Cross Slip of a Screw Dislocation.

Yeh bhi creep mechanism yahan pe hum dekhte hain. Abhi hum dekhte hain Climb of an Edge Dislocation jo bhi ek important mechanism hai creep deformation mein. To maan lete hain ki yahan pe ek obstacle hai aur yahan pe mera dislocation hai. Yeh slip plane pe move hoga aur aake is obstacle pe ruk jayega. To ek slip plane hai aur yahan par mein ek edge dislocation consider kar raha hoon. Edge dislocation ki jab baat karunga to tangent vector perpendicular Burgers vector rahega aur ek half plane is tarah se maine draw kiya hai. Abhi hum dekhenge ki yahan par ek obstacle hai aur jab high temperature aur time... mein sufficient time dunga aur stress apply karunga to yeh dislocation is...



dislocation move hoga is slip plane pe kuch is tarah se glide hoke yahan par aayega, yahan par ruk jayega is obstacle ke paas. Aur phir yahan par jab rukne ke baad kyunki yeh cross slip nahi ho sakta to iske paas ek hi mechanism available rahega ki climb ho is dislocation ka aur tabhi jaake yeh obstacle ko cross kar payega. To yeh jo climb hai woh diffusion controlled hai aur hum dekhte hain ki atoms diffuse kuch is tarah se honge is dislocation line pe. To humne dekha tha ki mere paas kuch edge dislocation hai aur humein pata hai ki mein jab creep ki baat kar raha hoon to mein high temperature ki baat karunga to ek equilibrium concentration of vacancies hogi. Yeh...

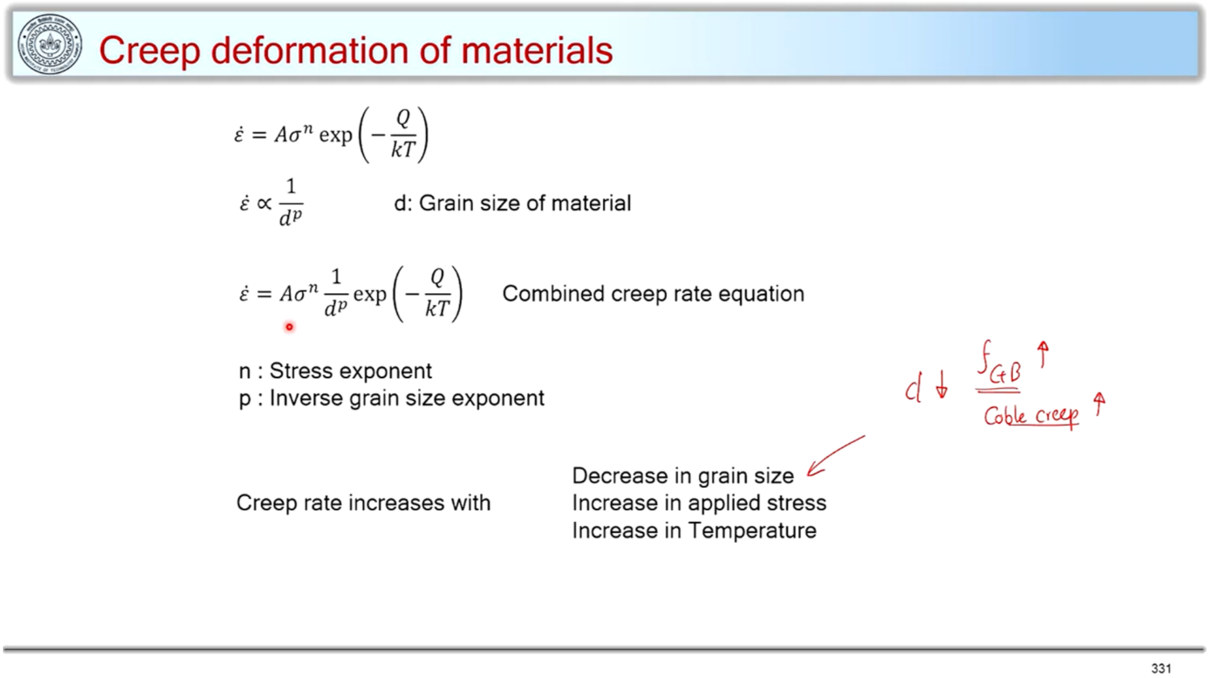
maine dislocation yahan pe mark kar liya, yahan pe ek extra plane hai aur maan lete hain ki vacancy kuch is tarah se taiyar ho gayi. To yahan par diffusion hoga aur diffusion hone ki wajah se wahan par climb hogi mere dislocation ki kuch is tarah se. To yahan par aap dekhenge ki kuch climb hoga locally aur yahan par dislocation is tarah se climb karega aur climb karne ke baad yeh obstacle ko cross slip... yeh obstacle ko yeh cross kar sakta hai. To is schematic mein is tarah se samajhte hain ki yeh dislocation yahan se yahan tak move hoga aur climb ki jab baat karunga tab woh climb in and out of the plane hota hai (yaani above hoga ya below hoga). To is tarah se yeh climb hoke cross kar lega is obstacle ko kuch is tarah...



se. To aap dekh pa rahe honge ki yeh is plane pe tha aur is parallel plane par jaake obstacle ko cross kar liya. Yeh ek climb hota hai edge dislocation ka jab mein creep ki baat kar raha hoon. To yeh do mechanism humne dekhe: diffusion mechanism aur dislocation based mechanism. Abhi hum Grain Boundary Sliding ki jab baat karenge to grain boundary sliding generally important role play nahi karti mere Primary aur Secondary creep mein. Yeh important role play karti hai Superplasticity mein. To hum superplasticity ke baare mein padhenge jaise-jaise hum aage badhenge. To generally yahan par mein ek schematic yahan par dikhana chahta hoon. Yahan par mere paas kuch grains hain aur maine...

kuch stress apply kiya aur aap dekh pa rahe honge ki yahan pe jo grain boundary sliding hai, yahan pe yeh jo boundaries hain is tarah se yahan pe jo shear stresses experience kar rahi hain, yeh boundary mein movements hogi ya slide hogi ek doosre ke upar. Aur slide kuch is tarah se hoga aap dekh pa rahe honge ki boundaries ek doosre ke upar slide hongi aur yahan pe net shape change is tarah se milega. Aap dekh pa rahe honge ki yahan pe ek shape change mila hai mujhe yaani ek strain mila hai is direction pe tensile stress ke direction pe. Aur yahan par aap dekh pa rahe honge ki yeh jo sliding ho rahi hai yahan par yeh boundaries par sliding ho rahi hai...

isko isliye hum grain boundary sliding kehte hain. Aur yahan par jo grains hain (do grains hain) inke beech mein compatibility maintain hai. Aap dekh pa rahe honge ki saare jo grains hain inke beech mein compatibility maintain hai yaani grain boundaries yahan pe intact hain. To yeh jo hota hai yeh kyun hota hai? Yeh do mechanism yahan par interplay karte hain. To yahan par simultaneously dono mechanism ka role hota hai: ek dislocation ka (dislocation creep mechanism) aur diffusion creep mechanism. Yeh dono creep mechanism operative rehte hain aur uske wajah se grain boundary ek doosre ke upar slide karke compatibility maintain karke shape change kar sakte hain. Yeh hai mera grain boundary...



sliding mechanism. Abhi mein creep deformation of material ki jab baat karunga tab kuch mathematical relation maine yahan par likha tha strain rate ki baat ki thi. To generally steady state creep rate hai aur maine kuch is tarah se relation likha tha stress ka dependence aur temperature ka dependence. Aur agar mein Grain Size (d) ki baat karunga to aap dekh pa rahe honge ki mein kuch is tarah se relation yahan par likh sakta hoon jo strain rate ka dependence hai grain size pe. To yeh inverse relation hai. Jaise-jaise mera grain size kam hota jata hai waise-waise strain rate (steady state creep rate) woh badhega aur yeh kuch power ke saath dependent hai mere grain size pe. Yeh 'p' ko mein Inverse Grain Size Exponent kehta hoon. To mein kuch is tarah se isko combine kar sakta hoon.

Jab mein microstructure ki baat kar raha hoon, yahan pe mere paas stress ki stress term hai, yahan pe temperature term hai, yeh dono humne combine kar liye. Aur yahan pe experimentally yeh bhi observe kiya gaya hai ki mera jo strain rate hai woh inversely proportional rehta hai mere grain size ke saath. Yaani jitna mera microstructure fine hoga waise-waise mera creep rate badhega aur woh is tarah se mein kuch relation likh sakta hoon. Jo 'p' hai isko mein keh sakta hoon Inverse Grain Size Exponent. To abhi hum dekhte hain ki creep rate kab-kab badhega? Creep rate badhta hai jaise...

decrease in grain size, increase in applied stress ya increase in temperature. To yeh grain size ka effect isliye aa sakta hai, aap samajh sakte hain jaise-jaise grain size ghatega waise-waise grain boundary jo fraction hai yeh badhega. Aur grain boundary jo agar fraction badh raha hai to mera Coble creep dominate kar sakta hai aur diffusion through grain boundaries badh sakta hai. Isliye jaise-jaise grain boundary fraction badhta hai ya grain size decrease hota hai waise mera ek diffusion mechanism dominate karne ki koshish karega. Yeh diffusion mechanism dominate karega to creep rate wahan par badhega. To yeh ho gaya dependence mere grain size jo ki microstructure...

parameter hai, aur stress aur temperature yeh dono mere applied experimental parameters hain ya application parameters hain. To yahan par humne dekha hai ki strain rate kuch is tarah se mein likh sakta hoon combined form mein. Ek simple relation mein yahan par likh sakta hoon, yeh bhi ek mera empirical relation hai. To is part mein humne dekha ki creep kya hota hai. Creep ek continued plastic deformation hota hai jo ki time ke saath hota hai aur constant stress par hota hai ya and constant temperature par hota hai. Creep ka humne dependence dekha stress ke saath, temperature ke saath aur microstructure parameter jo ki humne grain size ke saath dekha hai yahan par. Agle...

part mein creep baare mein aur jaanenge. Abhi ke liye yahin rukta hoon. Dhanyavaad.