**Mechanical behavior of materials**

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**Week-11**

**Lecture-58**

**Fracture & Theoretical Cohesive Strength of Materials**

Course Title
Mechanical Behavior of Materials (Hindi)

Lecture-57
Fatigue Stages and Paris Law

Namaskar, phir se swagat karta hoon aapka is course mein Mechanical Behavior of Materials jo ki hum Hindi mein padhenge. Last part mein hum fatigue ke baare mein padh rahe the. Is part mein hum dekhenge ki fatigue ke kya-kya stages hote hain aur ek law dekhenge Paris Law jo fatigue ke stages ko samajhne mein humein madad karega. To last part mein humne dekha tha yeh kuch fatigue failure hai material ka uska ek fractograph hai aur humne bataya tha ki yahan par hamara material ki crack initiation point hai. Yeh origin marks hamare fatigue failure of material ke liye aur yahan par jab ek critical stage pahunch jati
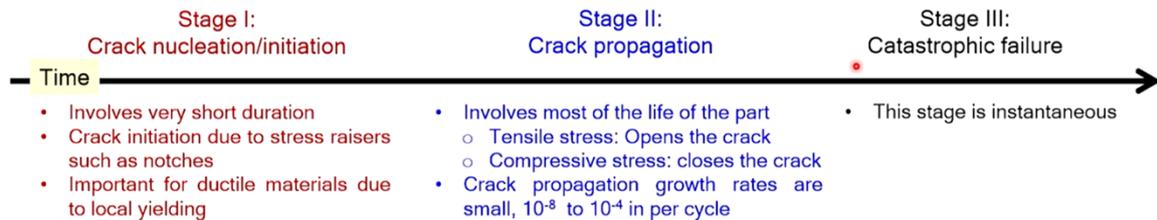
## Structural features of Fatigue
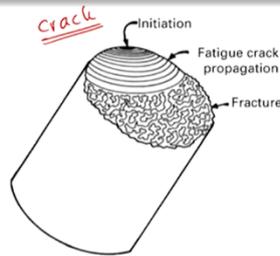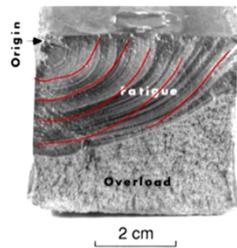
**Three stages of Fatigue**

- ❑ Crack Initiation
  - o Crack formation
  - o Micro-crack growth
- ❑ Crack propagation under cyclic load
- ❑ Final catastrophic fracture of the component

**Stage I:**
Crack nucleation/initiation

**Stage II:**
Crack propagation

**Stage III:**
Catastrophic failure

Time

- Involves very short duration
- Crack initiation due to stress raisers such as notches
- Important for ductile materials due to local yielding

- Involves most of the life of the part
  - o Tensile stress: Opens the crack
  - o Compressive stress: closes the crack
- Crack propagation growth rates are small, $10^{-8}$ to $10^{-4}$ in per cycle

- This stage is instantaneous

hai fatigue ke dauran to uske baad material us load ko le nahi pata ya material overloaded ho jata hai aur material fail hota hai. To yahan par aap dekh pa rahe honge ki yahan par maine ek origin mark kiya hai yahan par kuch marks aapko yahan par circular kuch aise dikh rahe honge, inko kehte hain beach marks. Iske baare mein bhi hum padhenge aaj ke part mein aur yeh marks kuch-kuch is tarah se darshate hain ki material fatigue se fail hua hai. To kuch-kuch stages dekhte hain iska schematic bana lete hain pehle. To is material mein pehle hum consider kar rahe the ki koi bhi defect nahi tha koi bhi crack nahi tha to yahan pe jo

initiation hai crack initiation ya crack nucleation process hogi Stage 1 mein aur uske baad yeh crack dheere-dheere cyclic loading ke dwara propagate hoga aur wo propagate hoke wo crack badhegi aur crack ek critical length tak pahunchegi aur is critical length ke pahunchne ke baad material catastrophic fail karega yaani ek speed se fail karega. Yahan par hum dekh pa rahe honge yeh jo material hai yahan pe yeh yeh jo region hai ye region ek to brittle ya ductile material ke hisab se yeh region behave karega. To janrally fatigue mein yeh jo plastic strain hota hai woh bahut negligible hota hai material ductile hai ya brittle hai to isliye jo failure hai woh hamesha catastrophic rehta hai.

Fractograph se dekha hai ki yahan pe ek initiation hai fatigue crack propagation hai aur yahan pe fracture hai. To abhi dekhte hain ki ye stages ko hum kis tarah se likh sakte hain. To teen stages mein hum likh sakte hain fatigue failure hota hai to pehla hai crack initiation, dusra hai crack propagation aur teesra hai fracture. Crack initiation ke do stages bhi likhte hain kuch-

kuch kitab mein aap dekhenge to ek crack formation aur micro crack growth. To yeh do stages bhi hum is mein crack initiation mein cover kar sakte hain ya include kar sakte hain. Abhi hum dekhte hain teen stages kaise-kaise aur kis tarah se inke mechanism hain. To main

time ke saath jab baat karunga yaani main material ko cyclic loading ke andar deform kar raha hoon ya kisi application mein main cyclic load material par lag rahe hain to time ke saath yaani us application time ke saath kya-kya stages honge fatigue ke hum dekhte hain. To humne teen stages dekh li Stage 1, Stage 2 aur Stage 3. To sabse pehla crack nucleation aur initiation, dusra crack propagation aur teesra catastrophic failure. To yahan par yeh jo baat kar rahe yeh mostly hum high cycle fatigue ke liye baat kar rahe hain number of cycles yahan par zyada hai. To yahan par is stages mein hum dekhenge ki yeh jo stage hai Stage 1 yeh bahut kam

duration ke liye operate hota hai ya active hota hai. Is stage mein aap dekhenge ki crack initiation ya nucleation un sites par honge yaani jahan par stress concentration zyada hoga material ke andar aur stress concentration kahan-kahan zyada hoga? Stress concentration zyada hoga notches pe, defects pe ya inclusions pe ya foreign particles pe ya hum dekh sakte hain ki is crack nucleation surface pe ho sakta hai. To yeh bahut important hai stage sabse zyada important hai jab hum ductile material ki baat karte hain kyunki yahan par hum dekhenge ki ductile material low yield hote hain. Jab hum fatigue ke baare mein baat rahe hain tab humne samjha tha ki fatigue jo hota hai woh yield

strength ke bahut neeche mein ya bahut kam values par fatigue failure hota hai. To isliye hum dekhenge ki local yielding yaani material locally yield kar raha hai jag main fatigue stress apply kar raha hoon. Iske baare mein bhi hum padhenge is part mein. Dusra stage hai mera crack propagation yaani ek baar crack nucleate ho gayi yahan par kuch is tarah se phir ye crack propagate hogi aur yeh jo stage hai ismein material ki most of the life spent hoti hai yaani yeh jo stage hai sabse zyada time leta hai is stage mein. Aur hum yeh dekh sakte hain ki jo agar tensile stress lag raha hai material pe kyunki hum cyclic load ki baat kar rahe hain to agar tensile stress lag raha hai to crack

open karenge aur compressive stresses hain to crack close karenge. To iske wajah se kya hota hai ki material mein crack opening aur closing hone ke wajah se aap dekhenge ki crack propagation growth rate jo hai woh bahut kam hota hai bahut small hota hai aur $10^{-8}$ to $10^{-4}$ per cycle hota hai. To yeh ho gayi hamari crack propagation stage aur teesri stage hai yeh catastrophic failure yaani aap dekhenge ki material mein critical crack agar yahan par develop

ho gayi kuch is tarah se aur yeh critical crack agar hum dekhenge is critical crack ki wajah se material mein ek load hum already apply kar rahe hain to material yeh us load ko le nahi payega aur uske wajah se material fail hoga aur yeh jo



## Stage I: Crack nucleation/initiation

Formation of slip bands in AlMg₃

N = 200
N = 500
N = 2000
N = 4500

HCF: most of fatigue life is spent on crack nucleation

W.A. Wood's concept

High cycle fatigue

Localized stress concentration: Inclusions/defects/cracks

Localized plastic deformation

Dislocation glide: Formation of surface steps

LCF: Roughening will be fast

slip bands

Stage I: cracks

Roughening of surfaces

Formation of surface cracks

- Accumulation of Extrusions and Intrusions on the surface
- Newly formed microcrack: Initially are loaded in Mode II (Shearing) and Mode III (Tearing) but not in Mode I (Opening)
- Surface finish and cleanliness of materials will thus affect their fatigue life

Mechanical Behaviour of Engineering Materials Metals, Ceramics, Polymers, and Composites: J. Rösler, H. Harders, M. Bäker

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stage hai woh instantaneous material ko fail karegi. Ye typical teen stages hain material ki jag material fatigue ke dwara fail hota hai. To sabse pehle stage dekhte hain Crack Nucleation yeh Stage 1 hai. To yahan pe kuch micrographs yahan pe dikhaye gaye hain ye is almg3 mein aap dekhenge ke surface pe jag main material ko different cycles ke after main dekh raha hoon ki yahan pe 200 cycle ke baad 500 cycle ke baad 2000 cycles ke baad ya 4500 cycles ke baad material ke usi area ke surface pe main dekh raha hoon. To aap dekh pa rahe honge ki yahan pe kuch slip bands bane huye hain. Aap dekhenge ki slip bands bante hain aur yeh slip bands yahan pe aap dekhenge ki

prominent hote ja rahe hain kuch is tarah se. Aap dekhenge ki ye slip bands yahan pe prominent honge aur kuch samay ke baad ye slip bands yahan pe crack nucleate karenge. To Stage 1 mein as number of cycles increase kar raha hoon to yahan pe slip bands banenge surface pe aake aur ye surface pe aake slip bands humein crack form karne mein madad karenge. To abhi dekhte hain ki yeh kis tarah se yeh mechanism hai. To maan lete hain mere paas yeh ek material hai aur iske upar main ek cyclic load apply kar raha hoon kuch is tarah se. Main cyclic load ke liye ye arrow yahan pe darsha raha hoon. To yeh agar main cyclic load apply karunga to yeh jo failure hai aur yeh jo stage hai hum

high cycle fatigue ke liye yahan par hum baat kar rahe hain. To high cycle fatigue ke dauran ye hamare paas cyclic load hai is cyclic load ke wajah se kuch-kuch jo defects hain mostly jaise inclusions hain, cracks hain ya foreign particles hain ye act karenge localized stress concentration. Hum jag fracture ke baare mein baat kar rahe the tab hum dekha tha agar koi defect hai material ke andar, main maan leta hoon kuch defect hai yahan par, to yahan par stress concentration zyada hoga. Humne dekha tha yahan par ki stress concentration is defect ke around zyada hoga. To aap dekh pa rahe honge ki locally yahan par yeh jo defects hain yeh stress

concentration badhayenge aur uske wajah se mere paas kuch localized plastic deformation milega kuch is tarah se. Yahan par plastic deformation hoga aur uske wajah se yeh cyclic loading ki wajah se yahan par yeh jo dislocation glide hoga. Agar yeh yeh defect nahi hai to dislocation bhi yahan par generate ho sakte hain aur ye dislocation glide hoke surface par aayenge. To is tarah se dekhte hain ki yahan par mere paas kuch dislocation yahan par generate huye aur yeh dislocations is cyclic loading ke dwara surface par aayenge aur surface par aake ek step taiyar karenge kuch is tarah se. Aur yeh jag step taiyar karenge to aap dekhenge ki pehle hamara material is tarah se

tha polish tha yeh material abhi rough ho gaya ya main yahan par keh sakta hoon ki smooth tha aur yahan par mera surface jo hai woh rough ho raha hai. Aap is micrographs mein bhi aap dekh sakte hain ki surface yahan par jaise-jaise number of cycles badh rahi hain waise-waise yeh surface rough hote ja raha hai. Abhi kya hoga kyunki cyclic loading ke dwara agar main tensile mein dislocation surface pe aake step taiyar kiye compression mein wo wahi baat follow nahi kar sakte isliye yeh surface rough ka rough rahega aur uske wajah se kya hoga yahan pe surface pe cracks banengi kuch is tarah se main crack dikha sakta hoon. To yahan pe ye surface crack taiyar hogi aur yeh surface crack abhi jaake phir baad mein jaake ye yahan pe bhi stress

concentration badhega aur ye jo mera yield strength hai uske kaafi neeche bhi main operate kar raha hoon to uske wajah se stress concentration ki wajah se ek crack aage badhega propagate hoga aur ultimately fail hoga. To ye pehle hum Stage 1 ki baat kar rahe hain to yahan pe yeh Stage 1 cracks ki main baat kar raha hoon. To kuch is tarah se samajhte hain mere paas kuch dislocations hain is material mein aur main yahan pe cyclic loading jag apply kar raha hoon to yahan pe slip bands taiyar honge yaani dislocation jo hai wo kuch is planes pe move hoke surface pe aayenge. To yahan pe aap dekh pa rahe honge ki yeh jo slip bands hain ye at a 45° majorly maine dikhaya hai

kyunki humein pata hai ki agar main yahan par is tarah se stress apply karunga to maximum jo shear hoga woh around 45° hoga. To aapko jo slip bands activate hoke milenge vo kuch is 45° angle ke saath milenge mere is load axis ke saath. To uske wajah se hum dekhenge ki surface pe aake step taiyar ho gaya aur jag cycle mein reverse honge agar ye tensile mein agar surface mein aake step ho gaya to compression mein dislocations wahi same path follow nahi kar paate uske wajah se surface yahan pe rough ho gaya. Aur main number of cycle jaise-ise badhaun waise-waise ye instances badhenge aur uske wajah se yahan pe surface rough hote jaake aage jaake yeh jo steps hain wo yahan pe crack

develop karega aur mujhe surface cracks milengi. To main kuch yahan pe likh pa raha hoon ki ye jo yeh jo steps jo yahan par banengi humne HCF ke liye baat ki thi LCF mein kyunki yahan par hum dekhenge ki low cycle fatigue mein stress high hota hai as compared to high cycle fatigue. To low cycle fatigue mein agar stress zyada hai to yeh jo roughing hai surface ka woh faster hoga. HCF ke kes mein most of the fatigue life mein yeh jo yeh jo Stage 1 hai yeh HCF ke kes mein nucleation crack nucleation mein most of the fatigue material ki life isi mein spend hoti hai. To aap dekh pa rahe honge ki yahan pe kaise hamare paas ek smooth surface tha aur

main number of cycle jaise-jaise badha raha hoon waise-waise yahan pe surface rough hoke cracks initiate huye. Woods mechanism se agar hum dekhenge to ye slip bands form huye aur iske wajah se yahan pe hum dekh pa rahe honge ki extrusion kuch is tarah se extrusion humein mile aur kuch intrusion surface pe milte hain yahan pe aap dekh pa rahe honge kuch intrusion. To iski wajah se humein crack milti hai aur inko hum kehte hain micro crack. To humne bataya tha ki ye jo slip bands taiyar huye wo 45° angle pe taiyar huye aur jo cracks taiyar honge vo near 45° angle pe rahengi. Aur humein pata hai ki agar ye crack is tarah se yaani micro crack is tarah se loaded hai to hum yahan pe dekh pa rahe honge yahan pe main

mark kar leta hoon ye 45° hai to aap dekh pa rahe honge ki yeh jo crack hai yeh mode 1 loading pe nahi hogi ye do load mein hogi do modes mein hogi jaise ki mode 2 aur mode 3. To yeh jo crack hai yeh opening mode mein loaded nahi hai. To initially yeh jo crack hai yeh sirf mode 2 aur mode 3 mein loaded rahegi. Abhi hum dekhenge ki humne ek ek baat ki thi ki localized stress concentration ki wajah se yahan par localized plastic deformation hoga ya higher increase in stress concentration hoga. To isliye hamara surface finish aur cleanliness yaani material mein koi inclusion ya defects na ho isko hum cleanliness kehte hain. To yeh jo surface finish aur cleanliness hai material ka yeh hamare fatigue
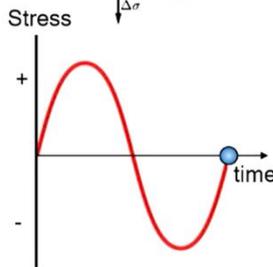
Stage II: Crack propagation
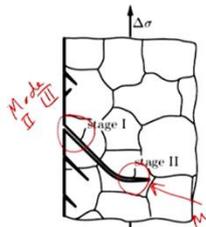
Propagation:
- Only cracks which reach favourably oriented slip systems, others are stopped
- With increasing crack growth, the stress at the crack tip increases until less well-oriented slip systems can be activated
- The crack to change its orientation to Mode I (from Mode II and Mode III)

- Tensile load: Small double notch at the crack tip concentrates the slip along 45° to the plane of crack
- The region near the crack tip yields: Plastic shearing
- The crack propagates stably, blunting the crack tip
- Compression: the slip direction in the end zones is reversed
- The elongated crack is compressed and resharpened.
- Cycle continues

Plastic zone
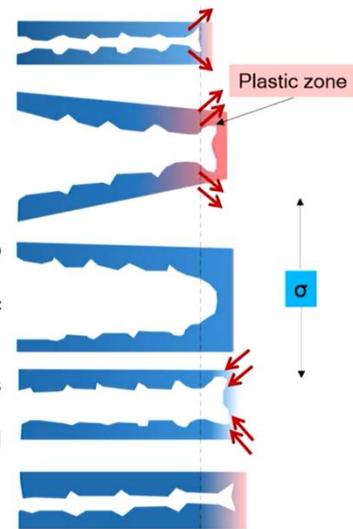
life ko determine karega ya affect karega. To jitna mera surface finish achha aur cleanliness achha utna material mein uska fatigue life achha. To yeh ho gaya Stage 1. Yeh jo concept hai yahan par humne explain ki thi ye Woods ki concept kehte hain isko aur Woods ne sabse pehle isko propose kiya tha jo extrusion aur intrusion surface par banengi aur uske dwara cracks banengi. Abhi hum doosri stage dekhte hain Stage 2 isko hum kehte hain crack propagation stage. Humne dekha ki surface par kuch cracks yahan par bani hain par aap dekh pa rahe honge ki kuch cracks yahan par ruk gayi hain surface par. To isko hum samajhte hain ki ye jo cracks hain

kuch cracks ye jag tak favorable slip system ke tab pahunchti nahi hain tab tak woh propagate nahi hogi wo wahan pe hi ruk jayegi kyunki in crack propagation ke liye humein zyada energy lagegi. To wahi cracks propagate hogi jo favorable oriented slip system mein pahunchi hai. Yahan pe aap dekhe honge ki ye jo cracks hain ek to yeh yahan pe favorable slip system nahi hai ya ye yahan pe aake grain boundaries ke dwara rok ki jayegi to yeh sari cheezein hoti hain. To kuch hi cracks propagate ho pati hain. To kaun si crack propagate hogi? Propagate hogi jo jis jahan par mujhe well oriented slip

system milegi. Aur aap dekhenge ki jaise-ise yeh well oriented slip system ke paas aa rahi hai, to jaise is stage mein aap dekhenge ki ye Stage 1 hai aur propagate hokar aap dekhenge ki material mein jag is tarah se orient ho jayegi favorable slip system ke taraf tab ye jo crack hai aap dekhenge ki yahan par yeh jo crack hai yeh opening mode mein convert ho gayi. Yahan

par mode 2 aur mode 3 tha yahan par bhi hum isko likh dete hain. To is initial first stage mein yeh mode 2 aur mode 3 mein loaded thi par yahan par aap dekhenge ki yeh iska mode change hokar mode 1 mein aa gayi hai. To jag mode 1 mein aati hai to aap dekhenge ki ye

crack opening mode hai aur crack yahan par open hokar propagate hogi. To isko samajhte hain ki crack Stage 2 ko kis tarah se opening hogi jag hum cyclic load apply karte hain. To maan lete hain mere paas kuch stress cycle is tarah se hai yahan pe tensile stress hai yahan pe compressive stress hai aur is tarah se meri cycle hai stress cycle hai. Aur maan lete hain main ek a yeh jo cyclic stress kuch is tarah se main denote kar raha hoon aur yahan pe mere paas material mein initial crack hai kuch is tarah se Stage 2 mein aa gayi hai woh crack aur abhi aap dekhenge ki iske wajah se jag hum stress ye cyclic stress aap experience karegi crack to kis tarah se crack open hogi close

hogi yeh dekhenge. To maan lete hain ki abhi main stress badh gayi yahan par to uske wajah se kya hoga yahan par aap dekhengi ki yeh abhi is direction mein force hai. To aap is direction mein agar force hai to aap dekhenge ki yahan par mujhe maximum shear stress milega aur iske wajah se kya hoga yahan pe a double notch taiyar hogi kuch is tarah se crack tip ke paas. To yahan pe aap dekhenge ki yahan pe slip concentrate ho gaya along 45°. To yahan pe humein kuch is tarah se double notch milega jag main aur stress badhata hoon kuch is tarah se. Abhi hum aaye yahan pe stress hamara badh gaya hai to hum dekhenge ki crack yahan pe open ho gayi hai aur kuch is tarah se hum dekhenge ki stress high hai to iske wajah se
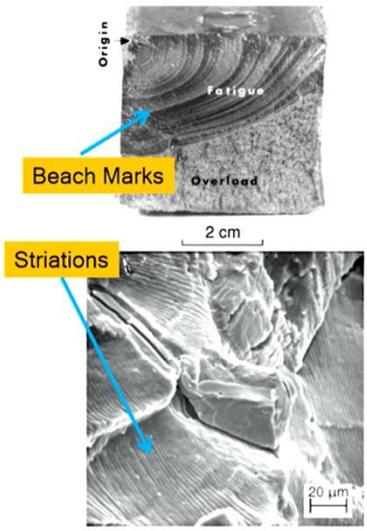
yahan pe kuch ek plastic zone kyunki crack ke aage ek plastic zone taiyar hoga kyunki stress concentration zyada hoga to yahan pe ye material pe ek plastic zone taiyar hoga aur yahan pe stress badhne ke karan crack open hogi. Aur yahan pe hum dekh pa rahe honge ki ye jo hai a crack badhegi because of plastic shearing. Yahan pe ek plastic shearing hogi yaani yahan pe zyada stress lag raha hai to yahan pe shear hoke ek crack aage badhegi aur aap dekh pa rahe honge ki jaise-jaise main stress badhaya waise-waise crack yahan par bhi open hogi aur yeh crack yahan par propagate hui. Abhi humein stress jag cycle mein dekh raha hoon to stress yahan par aaya to yahan

par stress relieve hua to iske wajah se kya hoga ki ye crack stable propagate to hui hai par yahan par aap dekh pa rahe honge ki yahan par yeh jo yeh jo region hai yeh blunt ho gaya. Ye blunt isliye hua kyunki yeh jo plastic zone hai yeh is crack ko propagate hone mein madad karega aur jaise hi stress yahan pe hat jayenge to yeh crack yahan pe blunt ho jayegi. Abhi hum

compressive region mein aa gaye to iske wajah se kya hoga ki crack close hoga kuch is tarah se crack close hoga aur aap dekh pa rahe honge ki yahan pe bhi shear stress lagenge par woh reverse direction mein shear stress yahan par lagenge aur uske wajah se bhi kya hoga yeh jo blunt tip thi

usmein kuch is tarah se double notch taiyar honge. To yahan par compression mein humein ek reverse ya ye jo end zones hain vo reverse ho jayenge yahan pe aur ek yahan par humein double notch milega. Ab jag main aur aage badhunga to yahan par yeh crack aur compress hogi aur yahan pe jo crack hai yeh resharpen ho jayegi. To jaise yahan par pahunchunga waise hi ye crack kuch is tarah se resharpened hoke kuch is tarah se ban jayegi. To aap dekh pa rahe honge ki yahan par ek cycle ke dauran kis tarah se crack open hui, close hui, blunt hui aur phir se resharpened hui. Aur ye mechanism continue hogi hamare fatigue deformation ke dauran. To aap dekh pa rahe honge ki yahan par ek reference line maine mark ki hai to aap dekhenge ki meri crack

## Stage II: Crack propagation

| Beach Marks | Fatigue Striations |
|---|---|
| • Macroscopically, Visible<br>• Seen with naked eyes | • Macroscopically, Invisible<br>• Cannot be seen with naked eyes<br>• Need microscope to see them |
| • Distance in mm | • Distance in 0.1 μm and 1 μm |
| • Due to change in loading conditions e.g., a change in the revolution speed, a short-time overload, or a machine downtime | • Depends on the load |
| • The arrangement of the beach marks often makes it easy to determine the position of the initial crack and the crack propagation direction | • An approximate measure of the crack propagation per cycle.<br>• Each striation is generated in exactly one cycle, but not every cycle does generate a striation |

tip yahan pe thi aur ek crack yahan par propagate hoke kuch is tarah se ban gayi hai. To yeh ho gaya mera crack propagation jo Stage 2 of fatigue hai. To Stage 2 mein hum dekhte hain ki humne dekha tha ki crack yahan par initiate huye. Abhi hum Stage 2 ke fractograph pe dhyaan dete hain to hum yahan dekh rahe hain ki kuch circular marks jaise yahan par hum dekh rahe hain beach marks. In circular marks ko humne kaha tha ki yeh fatigue ka signature hai aur isko hum kehte hain beach marks. Abhi hum yeh agar region ko aur magnify karke dekhenge

microscope mein to humein kuch is tarah se humein fractograph milega is tarah se humein microstructure milega. Yahan par bhi aap kuch marks is tarah se dekh pa rahe honge inko hum kehte hain striations ya fatigue striations.

To yeh do marks hain ye hamare typical marks hain hamare fatigue failure ke. To inke baare mein kuch jaante hain. To jaise main beach marks jag kahunga to ye beach marks jo hain ye humein naked eye se bhi dekhne ko milti hain jaise yahan pe aap scale dekh rahi dekhiye yahan pe 2 cm hai aur aapko ye naked eye se aapko dikhengi. Yeh jo striations hain ye aapko microscope mein jaake hi dekh dekhne ko milenge. Yahan par aap dekh pa rahe honge ki yeh scale jo hai 20 microns hai bahut-bahut small hai. To aap dekh pa rahe honge ki jo beach marks hain ye macroscopically visible hote hain aur fatigue striations jo hote hain vo microscopically invisible hote hain ye

naked eye se dekhe ja sakte hain beach marks. Fatigue striations hum naked eye se nahi dekh sakte. Inka distance jo hota hai aap dekhenge inka distance jo hota hai vo millimeters mein hota hai aur inka distance aap dekh pa rahe honge ki yeh microns mein hoga yaani 0.1 micron to 1 micron typically hota hai. Yeh beach marks kab taiyar hote hain? Yeh taiyar hote hain jag meri loading condition change ho rahi hai yaani kya-kya change ho raha hai jaise application mein revolution speed change ho sakti hai short overload ho sakta hai ya machine down time yaani aapne application mein rakha hai ek component aur machine ko humne band kar diya jaise weekend pe humne band kar diya to uske wajah se yeh beach

marks taiyar ho sakte hain. Fatigue striations yeh load pe depend karte hain yaani static load, cyclic load kitna change ho raha hai us hisab se yeh fatigue striations develop hote hain. To yahan pe yeh jo beach marks humein help karenge kya kis liye help karte hain? Humien beach marks humein batayenge ki crack initiation point kahan par tha ya direction of propagation kya thi. Fatigue striations humein identify karne ke liye strike propagation ka ek approximate measure hai ki crack propagation kaise ho raha hai each cycle. Ya aap dekhenge ki ek striation taiyar hone mein exactly ek cycle ki zaroorat hoti hai but zaroori nahi hai ki sab cycle mein striation taiyar ho par agar ek striation yahan par taiyar ho raha hai iska matlab woh ek paritcular cycle mein

taiyar hua hai. To yeh kuch difference hai beach marks aur fatigue striations mein. To yeh Stage 2 ke baare mein humne padha. Abhi jaise-jaise propagate hoti hai ek critical stage par pahunchegi aur hamara Stage 3 shuru hoga. To isko hum kehte hain fatigue crack growth ya

Stage 3 aur yahan par hum dekhenge ki material catastrophic fail hota hai. To yahan par hum kuch keh sakte hain ki jag ek crack critical length tak pahunchti hai tab jaake material fail hota hai kyunki crack propagate hui aur ek critical length achieve karegi aur uske baad crack uske baad material Stage 3 mein fail hoga. To hum jag hum crack ki baat kar rahe fracture toughness ki bhi baat kar sakte hain to

## Fatigue crack growth

**Stage III: Catastrophic failure**  Crack reaches critical length
Stress intensity factor = Fracture toughness

$$K = \alpha\sigma_{max}\sqrt{\pi a} \qquad K = K_{IC} \qquad \text{Fracture happens}$$

$k \to k_{IC}$

*A macroscopic crack that grow upon cyclic loading, then the fatigue life is determined by its propagation rate*

$K_{max} = \alpha\sigma_{max}\sqrt{\pi a}$

$\Delta K$

**If $\sigma_{min} < 0$, compression**

As the stress intensity factor is not defined in compression

$K_{min} = \alpha\sigma_{min}\sqrt{\pi a} \qquad K_{min} = 0$

$R < 0$   $\sigma_{min}$ Compressive   $k_{min} = 0$

$\Delta K = f(a/W)\,\Delta\sigma\,\sqrt{\pi a}$

**Where,**

$\Delta\sigma = \sigma_{max} - \sigma_{min}$   for $R \geq 0$
$\Delta\sigma = \sigma_{max}$   for $R < 0$

$\Delta K$ = stress intensity factor range ($K_{max} - K_{min}$)
$\Delta\sigma$ = stress range
$a$ = crack length
$R = \sigma_{min} / \sigma_{max}$ (stress ratio)

maine fracture toughness kuch is tarah se likha hai K = α σ max √(π a). α ek constant hai σ ek stress hai jo hum apply kar rahe maximum stress yahan par maine likha hai aur yeh function hai mere crack length ka. To aap dekhenge yeh jo value hai isko main kehta hoon stress intensity factor mere material ki aur yeh jo value fracture toughness ke equal ho jayegi tab apna material fail hoga aur tab fracture material ka hoga. Isko is tarah se samajhte hain humne bataya ki ek crack surface mein draw kar raha hoon yahan par ek crack initiate hui aur Stage 2 ke dauran crack propagate hogi. Is propagation ke wajah se mera stress intensity factor reach karega $K_1C$ tak aur tab jaake mera material

fail hoga aur yahan par is jag yeh reach hoga to material catastrophic fail hoga kuch is tarah se yaani ye sudden crack propagate ho jayegi poore thickness mein. To abhi isko samajhte hain cyclic loading ke dwara. To yeh jag hum baat kar rahe tab main macroscopic crack ki baat kar raha hoon yaani humne Stage 1 mein dekha tha ki microscopic cracks taiyar ho rahi hain par yahan par main jag baat kar raha hoon tab ye macroscopic crack ki baat kar raha hoon. Yeh

grow hogi meri cyclic loading mein aur yahan yeh jo fatigue life hai yeh determine karegi iske propagation rate ke dwara yaani crack kis tarah se propagate ho rahi hai woh

determine karegi meri fatigue life. To jag main cyclic loading apply kar raha hoon to kuch is tarah se. To yahan par dekh pa rahe honge ki yeh maximum stress hai isko main $\sigma$ max likha hoon aur yeh $\sigma$ min ye humne stress cycle dekhi hai hamesha. To iske corresponding hum K max aur K min nikaal sakte hain. To maan lete hain agar mere paas ek crack length hai aur ye maximum stress hai to main K max kuch is tarah se likh paunga $\alpha$ $\sigma$ max $\sqrt{(\pi a)}$ aur $\sigma$ min ke liye main likh paunga K min = $\alpha$ $\sigma$ min $\sqrt{(\pi a)}$. Abhi yeh jo compression agar is stress ko main compressive stress maan ke chal raha hoon agar ye $\sigma$ min yaani < 0 hai to

yahan par ye stress intensity factor defined nahi hai to isliye is K min ko main shunya keh sakta hoon ya zero keh sakta hoon. To yeh K min ki value main zero kahunga jag yeh $\sigma$ min negative hai ya < 0 hai compressive stress hai. To main ek $\Delta$K ki value likhunga. $\Delta$K ki value kya hai? K max − K min. To ye ho gayi meri $\Delta$K ki value agar main isko consider karunga yeh $\Delta$K ho gaya jo difference hai mere K max aur K min ka aur isko main keh sakta hoon ye ek function hai mere crack tip ka yeh factor hai constant hai yeh crack tip ka ek function hai aur yeh ho gaya $\Delta\sigma$ $\sqrt{(\pi a)}$. To

yahan pe kuch yeh parameters define kar dete hain jaise $\Delta$K hai yeh ho isko main kahunga stress intensity factor range ye ye meri stress range thi yaani $\Delta\sigma$ meri stress range hai to yeh jo range hai yeh stress intensity factor range hai isko main kahunga K max − K min aur $\Delta\sigma$ stress range hai aur a meri crack length hai. Abhi ye $\Delta\sigma$ ki value kuch is tarah se main likh paunga jaise $\Delta\sigma$ = $\sigma$ max − $\sigma$ min jag R ≥ 0 hai aur $\Delta\sigma$ = $\sigma$ max hoga jag R < 0 hai. R kya hai? Humne dekha tha ki R ek stress ratio hai ye ratio kiska hai $\sigma$ min / $\sigma$ max.

To hum dekh pa rahe honge ki R ki value jag positive hai R > 0 hai to hum $\Delta\sigma$ ki value isse replace karenge aur R ki value < 0 hai to $\Delta\sigma$ ki value hum is tarah se replace karenge yaani iska matlab kya hai ki jaise hum is tarah se likh sakte hain compress kyunki jag R ki value negative hai < 0 hai to $\sigma$ min hamesha compressive rahega aur compressive ke liye hum is K min ki hum

K min ki value yahan par shunya lete hain isliye yeh condition yahan par likh rahe hain. To yeh ho gaya mera stress range stress intensity factor range aur is
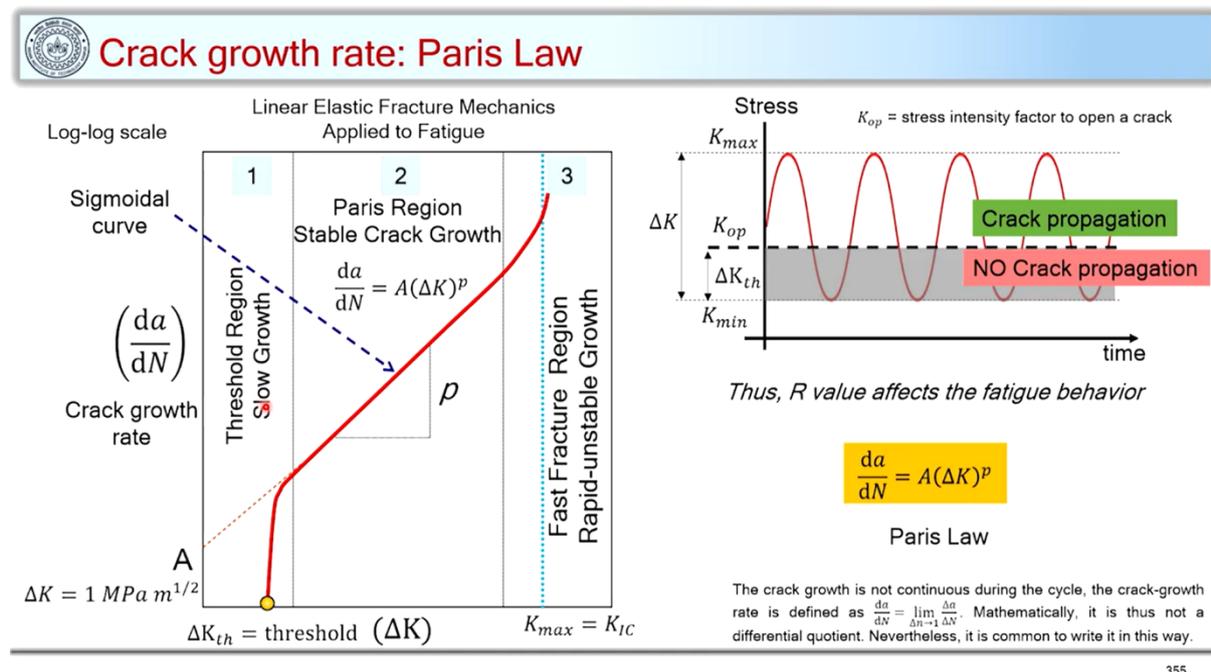


stress intensity factor range se main crack propagation rate determine kar sakta hoon. Yahan par aap dekh pa rahe honge ki mujhe ek relation mil raha hai ΔK ka a ke saath aur ek stress range ke saath. To hum dekhte hain ki crack propagation rate hum kis tarah se determine kar sakte hain. To iske liye hum consider karte hain linear elastic fracture mechanics jo hum apply karenge fatigue life ke liye. To jag main crack growth rate ki baat karunga tab main crack growth rate kuch is tarah se define karta hoon da/dN. To yahan par yeh jo hai change in crack length per cycle is tarah se main isko define kar sakta hoon. To yahan pe mathematically kuch is tarah se likha hai par

actually actual definition iska hum is tarah se likh sakte hain ki change in crack length per change in cycle. To yaani har cycle ke dauran crack growth hoti nahi hai isliye hum isko Δa / ΔN likhte hain. To ye mathematically quotient nahi hai but janrally fatigue analysis mein hum yahi term istemal karte hain. To main yahan pe crack growth rate kuch is tarah se likh raha hoon da/dN aur yahan par ΔK x-axis pe plot kar raha hoon aur ye log-log scale mein hum likhte hain. To mujhe kuch is tarah se behavior milta hai kuch is tarah se mujhe curve milta hai aur yeh kind of sigmoid curve hai. Agar main is curve ko dekhunga achhe se to yahan par main is curve

ko teen part mein divide kar sakta hoon kuch is tarah se aap dekh pa rahe honge maine yahan par slope ke dwara is teen part ko yahan par divide kiya hai. First part, second part aur third part. To isko hum kehte hain Stage 1, Stage 2 aur Stage 3. To yeh jo yahan par hum crack growth rate aap dekhenge yeh point par, to yeh point par crack growth rate minimum hai aur bahut kam hai yahan par to hai hi nahi. To aapko ek threshold stress intensity factor range lagegi jo aapke crack growth ko propagate karegi yaani ek minimum value humein chahiye. To isko is tarah se samajhte hain ki mere paas kuch stress cycle hai is tarah se yahan par

maine K max mark kiya yahan par maine K min mark kiya aur aapko crack propagate karne liye ek yeh jo hai yeh $\Delta K$ hai aur crack propagate karne ke liye mujhe ek stress intensity factor lagegi value lagegi jo mere crack ko open karegi. To ek minimum value yaani isko main operating stress intensity factor kahunga isliye isliye isko K op likha hai. To yeh value typical yahan pe maine mark ki hai. To is tarah se samjhiye ki ye is stress cycle main apply kar raha hoon to mujhe ek minimum value chahiye jo mere crack ko open karegi. Iska matlab yeh hai ki yeh jo cycle ka yeh part hai is K op ke upar wahi crack ko propagate karne mein madad

karega aur yeh jo part hai neeche wala yeh crack ko propagate karne mein madad nahi karega yaani crack ko open nahi karega to ye propagate karne mein madad nahi karega. To humein ek minimum value chahiye K op ki aur isi value ko hum kehte hain yeh jo $\Delta K$ th yeh minimum aap jag apply karenge tabhi jaake crack propagate hogi jag cyclic loading hogi tab. Isko hum kehte hain $\Delta K$ th ya threshold stress intensity factor. To yeh yahan par humne mention kiya jag hum isko cross karenge tabhi jaake crack yahan par propagate hona chalu karegi aur crack growth rate humein dikhega. To is observation se hum yeh keh sakte hain ki R value jo hai vah

hamare fatigue life ko affect kar sakti hai. Abhi hum dekhte hain to aapko main exercise deta hoon ki aap dekhiye ki R value ka kya effect hai is sigmoidal curve pe. To pehli stage hum dekhenge yahan par jag main jag yahan par pahuncha hoon to yahan par aap dekhenge ki isko main kehte hoon threshold region. Yahan par jo crack propagation rate hai crack growth rate hai vah bahut slow hai isko slow growth region bhi kehte hain. Doosra region aap dekhenge is region ko main kuch is equation se likh sakta hoon. Ek linear relation agar main likhunga to isko likhunga ye crack growth rate = $A(\Delta K)^p$.

Yeh jo region hai isko main kehta hoon Paris region aur yahan par aap dekh pa rahe honge ki ye crack jo hai vo stable grow ho rahi hai jaise-jaise mera $\Delta K$ yahan pe increase ho raha hai ye linearly yahan pe vary ho rahi hai. To aap dekh pa rahe honge isko main kehta hoon stable

crack growth region aur teesra region aap dekhenge aur yahan par maine Paris Law ye Paris ke naam par likha gaya hai ye Paris Law hai aur iska hum istemal karenge ki number of cycles find out karne aur crack length find out karne mein. To ye hai mera Paris Law. Yahan pe aap dekh pa rahe honge ki ye stable crack grow karegi. Teesre region mein hum jag jayenge tab aap dekhenge ki crack yahan tak propagate ya

crack grow ho gayi is tarah se. To aapka ye jo K max hai ye pahunch jayega aapke fracture toughness ke value K_c tak aur yahan pe aap dekh pa rahe honge ki iske baad material catastrophically fail hoga yaani K max ki value jag $K_1C$ aa jayegi pahunch jayegi tab aap dekhenge ki material fail hoga aur yahan par mujhe fast fracture milega. Aur yeh jo crack growth hai yeh unstable rahega yaani isko main control nahi kar paunga ye rapid hoga unstable growth of crack mujhe yahan pe milegi. Abhi main Paris Law ko jag dekh raha hoon ya Paris equation ko yahan par dekh raha hoon tab A ki value, p ki value to yeh slope hogi yeh maine mention kiya tha iska

## Paris Law

- Applied stress intensity factor ($\Delta K$) < Threshold ($\Delta K_{th}$) implies no fatigue crack growth.

- Fatigue crack growth life is found by integrating the Paris equation between a known (or assumed) initial crack length and a maximum acceptable crack length.

$$\frac{da}{dN} = A(\Delta K)^p$$

$$N_f = \int_{a_0}^{a_f} \frac{da}{A(\Delta K)^p} = \frac{1}{A\sigma_r^p \pi^{1/2}} \int_{a_0}^{a_f} \alpha(a)^{-p} a^{-p/2} da$$

Initial crack size ($a_o$) is usually found by inspection/or is assumed a minimum crack length,

Critical crack size ($a_f$) is found from

$$a_f = \frac{1}{\pi}\left(\frac{K_c}{\alpha\sigma_{max}}\right)^2$$

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agar main slope loonga da/dN aur $\Delta K$ log–log scale pe jag main plot karunga tab mujhe ye slope jo milega tab mujhe slope ki value p rahegi. Aur yeh jo value rahegi A ki value yeh intercept rahegi is y-axis par jag $\Delta K$ ki value main 1 MPa√m consider karta hoon. To yeh ho gaya mera ek constant intercept on y-axis. To ye ho gayi crack growth rate jag humne jo humne Paris Law se samjhi. Paris Law ko aur achhe se samajhte hain. Jag main

stress intensity factor ΔK yeh kam rahega threshold stress se tab meri koi fatigue crack growth nahi hogi. Doosra point hum Paris Law se yeh samajh

sakte hain ki yahan se hum ek maximum acceptable crack length determine kar sakte hain jo fatigue life ko bhi determine karne mein meri madad karega. To agar main Paris Law kuch is tarah se likhta hoon aur main agar yeh number of cycles jo failure ke liye lagegi vah kuch is tarah se main determine kar sakta hoon. Is equation ko main agar integrate karunga yahan par aap dekh pa rahe honge maine yahan par is part ko integrate kiya kahan se kahan tak? Yeh $a_0$ agar meri initial crack length hai aur a_f yeh meri final ya fracture ki crack length hai. Agar yeh donon mujhe pata hain wahan tak agar main integrate karta hoon is relation ko aur mujhe p pata hai ΔK pata hai ΔK ko main convert kar sakta hoon

stress range ke saath, a pata hai tab main number of cycles to failure determine kar sakta hoon. Aur iska equation main yahan par derivation yahan par de nahi raha hoon aap is book ko refer kar sakte ho G. Dieter ko Mechanical Metallurgy ke aur yeh relation aapko milega. Is relation se aap yeh dekh sakte hain ki N_f jo hai number of cycles to failure hai ye ye stress range σ_r jo hai isse inversely proportional hai. Aur aap dekh pa rahe honge ki yeh yeh inverse proportional to crack length bhi hai kyunki yahan par −p/2 power hai to aap isko solve karenge to aapko yeh milega ki jaise–jaise jitni badi crack length hogi utni number of cycles meri kam hogi aur jitna stress range zyada utna

bhi number of cycles mere failure to kam ho jayegi. Yeh ek geometric factor hai mere crack length ka. To yeh ho gayi meri number of cycles. Aap usi tarah se agar mujhe initial crack length pata hai yaani yeh main kisi inspection ke dwara nikaal sakta hoon jaise ultrasonic methods hain ya different non-destructive testing hain usse main initial crack length material ki determine kar sakta hoon. Aur main final crack length isi equation ko agar main solve karunga to mujhe ek final crack length ya fracture jag critical crack length crack size agar mujhe determine karni hai to yeh equation mujhe ek critical crack length dega. To yahan par bhi aap

dekh pa rahe honge ki yeh jo critical crack length hai yeh agar mera K_c yaani stress intensity factor jitna zyada hai to utni badi mujhe crack lagegi propagate karne mein. σ max agar zyada hai ya maximum stress agar main badha raha hoon material pe to yeh jo crack length lagegi vo

kam lagegi mujhe yaani iska matlab agar $\sigma$ max badh raha hai to small crack mein hi mera material catastrophically fracture ho sakta hai. To yeh darshata hai ki material ki properties fatigue life mein bahut mahatva rakhti hain. To yeh ho gaye teen stages. To is part mein humne fatigue ke different stages dekhe fatigue ke different stages

humne fractography par kiya the jaise crack initiation, crack propagation aur failure ya catastrophic fracture. Aur inke different mechanism dekhe humne kis tarah se crack initiate hoti hai surface par aur vah kis tarah se propagate hoti hai usko humne Paris Law se samjha aur Paris Law se hi humne number of cycles to failure aur ek critical crack size ko determine kiya hai. To abhi ke liye hum yahi rukte hain. Dhanyawad.