Applications of SEM in Failure Analysis

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Failure Mechanisms, Characterization of damages in materials: Fractography, Energy Dispersive Spectrometry (EDS)
Outline...

- Introduction
- Classification of fracture
- Fracture features
  - Macroscopic
  - Microscopic
- Identification of fracture modes
- Applications
  - Examples from failure analysis
- Conclusions
Fractography: definition

- Fractography is the study of fracture surfaces of materials
  - Signatures of fracture process
  - Characteristic features

- Examination of fracture surfaces to determine mode and cause of fracture
  - Macroscopic features: smoothness and markings observable with naked eyes or optical microscope
  - Microscopic features: detailed information by using electron microscope
Fractography: objectives

- Mode of fracture
  - Fatigue
  - Stress corrosion cracking
  - Hydrogen embrittlement etc

- Reason for crack initiation
  - Stress concentration
  - Material defects
  - Corrosion etc

- Study of crack growth rate

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Fracture in metals

- Non-fluctuating stresses
- Fluctuating stresses
Fracture in metals

- Non-fluctuating stresses
  - Mechanical or overload: tension, compression, bending, torsion, shear......
  - Chemical: stress corrosion, hydrogen embrittlement, liquid metal embrittlement, exfoliation......
  - Thermal: creep......
Fracture in metals

- Fluctuating stresses
  - Mechanical or overload: fatigue (HCF, LCF), fretting, fretting-fatigue, wear......
  - Chemical: corrosion fatigue.....
  - Thermal: fatigue......
Fracture in metals... *engineering importance*

- **Mechanical**
  - Ductile, brittle, fatigue

- **Environmental**
  - Corrosion, corrosion-erosion

- **Mechanical-environmental**
  - Stress corrosion cracking, hydrogen embrittlement, corrosion fatigue
Fracture in metals... *engineering importance*

- Static overload fracture
  - Ductile, brittle

- Progressive fracture
  - Fatigue, stress corrosion cracking, hydrogen embrittlement, stress-rupture
## Failure in metals... statistics

<table>
<thead>
<tr>
<th>Failure mode</th>
<th>% of failures</th>
<th>Engineering components</th>
<th>Aircraft components</th>
</tr>
</thead>
<tbody>
<tr>
<td>Corrosion</td>
<td>29</td>
<td>29</td>
<td>16</td>
</tr>
<tr>
<td>Fatigue</td>
<td>25</td>
<td>25</td>
<td>55</td>
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<tr>
<td>Brittle fracture</td>
<td>16</td>
<td>16</td>
<td>-</td>
</tr>
<tr>
<td>Overload (ductile)</td>
<td>11</td>
<td>11</td>
<td>14</td>
</tr>
<tr>
<td>High temp. corrosion</td>
<td>07</td>
<td>07</td>
<td>02</td>
</tr>
<tr>
<td>SCC / Corrosion fatigue / HE</td>
<td>06</td>
<td>06</td>
<td>07</td>
</tr>
<tr>
<td>Creep</td>
<td>03</td>
<td>03</td>
<td>-</td>
</tr>
<tr>
<td>Wear/abrasion/erosion</td>
<td>03</td>
<td>03</td>
<td>06</td>
</tr>
</tbody>
</table>
Fracture in metals

- Ductile fracture
  - Ductile fracture involves gross plastic deformation and *less catastrophic*
  - Substantial energy is absorbed by microvoid coalescence (*high energy fracture mode*)

- Brittle fracture
  - Brittle fracture does not involve gross plastic deformation and *catastrophic*
  - Low energy is absorbed during fracture (*low energy fracture mode*)
Ductile fracture... *macroscopic*

- Ductile fracture is less serious problem in engineering... plastic deformation

- Under uniaxial tensile force, after necking, *microvoids* form and coalesce to form crack, which then propagate in the direction normal to the tensile axis

- The crack then rapidly propagate through the periphery along the shear plane at 45° resulting in cup and cone fracture
Failure Mechanisms & Fractography

Ductile fracture...macroscopic

Microvoids are easily formed at inclusions, intermetallic or second phase particles and grain boundaries.
Ductile fracture...microscopic

Dimple rupture
Ductile fracture...microscopic

Random planar array of particles acting as void initiators

Growth of voids to join each other as the applied stress increases

Linkage or coalescence of voids to form free fracture surface
Ductile fracture... microscopic

- Decohesion at particle-matrix interface
- Fracture of brittle particles
- Decohesion of interfaces associated with shear deformation or grain boundary sliding

2024 Al-alloy
Steel
Ductile fracture...microscopic

Tension

Torsion
Ductile fracture... *dimple shapes*

Fractography
ASM Handbook
Ductile fracture...microscopic

Structural steel

Bearing steel
Brittle fracture...macroscopic

- Brittle fracture is a serious problem in engineering.....no or negligible plastic deformation *(catastrophic in nature)*
  - Cleavage
  - Intergranular

Chevron marks
Cleavage fracture ……microscopic

- Cleavage fracture surface is characterized by flat facets (size normally similar to grain size)
- River lines or stress lines are steps between cleavage on parallel planes and always converge in the direction of local crack propagation
Intergranular fracture is moderate to low energy brittle fracture mode resulting from grain boundary separation.

- Weak grain boundaries, grain boundary segregation, embrittlement.
Progressive fracture

- Fatigue
- Stress corrosion cracking (SCC)
- Hydrogen embrittlement (HE)

Crack initiation followed by progressive propagation over a period of time under fluctuating load or sustained tensile load
Progressive fracture... macroscopic

Static overload failure

Progressive crack propagation
(Crack arrest marks/beach marks) – can be fatigue or SCC or HE

Crack origin
Progressive fracture......crack origin
Progressive fracture......crack origin
Progressive fracture...crack origin

Differential exposure to environment
Progressive fracture......crack propagation direction

Beach marks/clamshell marks
Fatigue fracture......*mechanisms*

Cracks that cause fatigue fracture almost always initiate/nucleate at *component surface* at some stress concentrations; scratches, dents, fillets, threads, weld beads/spatter........

- **Stage I** Propagation
  - Crack tends to grow initially along crystallographic planes of high shear stress: *high stresses and notches tend to shorten this stage*
  - It may propagate only over *a few grains*
  - Length of stage I is controlled by presence of stress raisers such as:
    - ........................................
    - ........................................
- **Stage II** Crack growth rate increases *(perpendicular to tensile stress direction)*
  - *Mostly transgranular crack propagation*
Fatigue fracture......mechanisms

- Double notch at crack tip, extends along shear plane under tensile loading and then blunts due to deformation.
- Compression closes cracks and shear occurs in opposite sense leading to sharp notches again.
- And then again and again.................
- The process leaves markings on the fracture surface; Beach Marks and/or Striations.
- Indicate position of crack tip at some point in time.
Fatigue fracture...... Foolproof signature

Stainless steel  Hardened steel
Fatigue fracture...... Foolproof signature

2024 Al-alloy

Ti-6Al-4V
Fatigue fracture......*signatures*

Ni-base superalloy (DS)
Fatigue fracture......signatures
Progressive fracture...... micro-mechanisms

Fatigue or SCC or HE????

Dimple rupture

Intergranular (SCC, HE)

Crack initiation

Fatigue striations
Conditions for SCC and HE cracking

**SCC**
- A susceptible alloy
- Aggressive environment
- Applied or residual stress

**HE**
- A susceptible alloy
- H$_2$ in the material
- Applied or residual stress
SCC......mechanisms and prevention

Sources of Stress for SCC

<table>
<thead>
<tr>
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<th>Applied</th>
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<tbody>
<tr>
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</tr>
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</tr>
<tr>
<td>Machining (Lathe-Mill-Drill)</td>
<td>Vibration</td>
</tr>
<tr>
<td>Heat Treating</td>
<td>Rotation</td>
</tr>
<tr>
<td>EDM, Laser/Wire Cutting</td>
<td>Bolting</td>
</tr>
<tr>
<td>Grinding</td>
<td>Pressure</td>
</tr>
<tr>
<td></td>
<td>Dead Load</td>
</tr>
</tbody>
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Proper selection of material
Removing the corrosion species that promotes SCC
Change the manufacturing process or design to reduce the residual tensile stresses
Surface protection to avoid corrosion

Stress Corrosion Cracking Triangle

Failure Mechanisms & Fractography
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**HE...mechanisms and prevention**

**Sources of hydrogen**
- Melting (generally causes blistering)
- Environment (H₂O during welding)
- Surface treatment
- Surface cleaning
- Plating
- ......

**Sources of Stress for HE**

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**Hydrogen embrittlement Triangle**

- Use material with lowest hardness in the specification range
- Use clean steel (free of MnS inclusions...)
- Baking as per the ASTM specification
- Baking must be performed immediately after the processes where possibility of hydrogen pick up in the component exist
SCC and HE...... *How to distinguish?*
SCC and HE...... *How to distinguish?*

Corrosion pit

100µm

SCC

HE

Failure Mechanisms & Fractography
Applications

Engineering Failure Analysis...

- Case History I  Microstructural degradation
- Case History II Corrosion leading to fatigue
- Case History III HPTR blade engine bed failure
- Case History IV StressRupture leading to fatigue.ppt
- Case History V Fretting_bolt_pipeline.ppt
- Case History VI Hydrogen embrittlement.ppt
- Case History VII Blade cavity
Conclusions

☐ Study of fracture surface provides information about how the material/component fractured
☐ Behaviour of the material/component under service conditions
☐ Mandatory for engineering failure analysis
☐ Research in materials science
  ■ Fracture-path studies
  ■ Deformation before and during fracture
  ■ Fracture-surface characteristics
    ☐ Estimation of grain size
    ☐ Weak micro constituents etc

☐ Many more..........................