Failure Analysis

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Failure Analysis

Goal: Understand why failure occurred to prevent it from happening again!

• Why it’s so important – lessons learned
• Consequence of failure – financial impact? Bodily harm? Space mission?
• Can also be applied pro-actively instead of reactive to enhance fatigue life
Failure Analysis - Procedure

• Background information is critical!!
  – Application environment – Test, field, over stress condition, dynamics, temperature, etc.
  – Expected life vs. life at failure – achieving 90% of required life much different than 10%
  – History – does this part frequently fail in this test environment, or no failures for years?
  – Material grade / quality level – valve quality wire? Commercial quality?
  – Manufacturing process flow – not always obvious from analysis what operations were performed
Failure Analysis
Typical Procedural Flow

1. Macroscopic visual examination and documentation
2. Stereo microscope examination and documentation
3. Scanning Electron Microscope
4. EDS (Energy Dispersive Spectroscopy) elemental identification
5. Metallography microstructure analysis
6. Hardness / microhardness analysis
7. Residual stress measurement with X-ray diffraction
In General, 4 factors influence fatigue life of ANY part:

1. Material strength (UTS, yield point, grain size, micro)
2. Residual stress (from forming, heat treat, shot peen)
3. Geometric stress concentrators (defects, etc.)
4. Applied stress (static, dynamic, Hertz stress)
Failure Analysis
“Four Fatigue Factors” Approach

Applied Stress

Material Strength

Stress Concentrators

Residual Stress

Material: AS-33

Residual Stress vs. Depth

Applied Stress

Material Strength

Stress Concentrators

Residual Stress

Material: AS-33
The scanning electron microscope (SEM) uses a focused beam of high-energy electrons. These electrons interact with the sample, producing various signals that can be used to obtain information about the surface topography and composition.
X-Ray Diffraction

- X-Ray Diffraction (XRD) can be used to measure the residual stress in a sample using the distance between crystallographic planes.
- A monochromatic ($\lambda$) x-ray beam impinges upon the sample which has an ordered lattice spacing ($d$-spacing) and constructive interference will occur at an angle ($\Theta$).
- When material is in tension, the $d$-spacing increases, when under compression, the $d$-spacing decreases. These changes in the $d$-spacing translate into changes in the diffraction angle $\Theta$ measured by the x-ray detector. Stresses can be determined using Bragg’s law.

**Bragg’s Law:**

$$n \lambda = 2d \sin \theta$$

The path length difference between x-rays hitting parallel atomic planes must be a multiple of their wavelength.

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Failure Analysis Case Histories

- **ID Cracking**
  - Traditional coiling crack
  - Embrittled wire crack

- **Corrosion Failures**

- **Sub-surface high stress fatigue**

- **Raw Material Defects**
ID Cracking – Frictional Coiling Crack
ID Cracking – Frictional Coiling Crack

- Under stereomicroscope analysis, the fracture initiates on the spring ID at a *small* crack, transverse to the wire direction.
- The crack most often has a blue/brown-tint, because it was created during or after coiling and then exposed during stress relieve.
- Friction from the coiling arbor locally heats the wire, reducing the tensile strength and the resistance to crack initiation (normal for a single point coiler).
- A tool mark is commonly present on the wire surface in line with the crack.

**Primary contributing factors:**
- Wire oxide coating
- Wire UTS
- Tooling setup
- Tooling wear (surface roughness)
- Spring Index
ID Cracking – Frictional Coiling Crack
ID Cracking – Frictional Coiling Crack

- A tool mark is commonly present on the wire surface in line with the crack.
Samples lightly HCl etched, then heavily nital etched. Martensite in tool mark is visible.

Untempered martensite within tool mark on failure with coiling cracks.
ID Cracking – Embrittled Wire

• Under stereomicroscope analysis, the fracture initiates on the spring ID at a *large* crack (approximately 1/3 if the wire diameter), transverse to the wire direction.

• These cracks were formed due to embrittlement of the raw material combined with coiling conditions on a single point coiler.

  – The normal tensile residual stress from coiling combined with the embrittled material to form cracks on the spring ID. The cracks grow until they run out of a driving force, i.e. until the residual stress is relieved during the stress relieve heat treatment.

  – Embrittlement (the residual stress was acting on a wire with a high hydrogen content which was not able to resist crack propagation)

  – Additionally, the normal friction from the coiling arbor locally heated the wire, reducing its tensile strength and resistance to crack initiation.
ID Cracking – Embrittled Wire
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ID Cracking – Embrittled Wire
Scanning electron microscope analysis shows the presence of a highly intergranular fracture morphology in the oxidized transverse crack region.
ID Cracking – Induced Hydrogen Embrittlement

• An as-coiled spring (with high tensile residual stress from coiling) was placed in a beaker of hydrochloric acid.

• Numerous *large* cracks form along the spring ID
Rust / Corrosion

Corrosion on 1095 Flapper Valve

Steel is not thermodynamically stable - driving force is to become iron oxide.
Corrosion Assisted Fatigue
Corrosion Assisted Fatigue

- Corrosion formed after manufacture was complete
Corrosion Assisted Fatigue

- Corrosion created in the application
Corrosion Related Failures

- Corrosion created in the application
  - corrosion appeared sharp around the edges, indicating that the corrosion was formed after manufacture was complete
Corrosion Assisted Fatigue

- Corrosion created in the application

- Sharp and fresh red rust

- Corrosion on fracture face

- Initiation
Corrosion Assisted Fatigue

- Corrosion created in-process
  - corrosion appeared rounded around the edges, indicating that the corrosion formed on the raw wire or during manufacturing, before finishing processes

Shot peened over corrosion
Sub-surface High Stress Fatigue
Fatigue Analysis

“Net” Stress Concept

Summation of applied and residual stresses

Max Stress vs. Depth

Diagram showing the summation of applied and residual stresses with depth. The graph illustrates the relationship between stress (ksi) and depth (inches below ID surface) for various stress conditions.
Sub-surface High Stress Fatigue

Depth below ID, 0.001”
Sub-surface High Stress Fatigue

Shear plane initiation site corresponds with depth of no residual compression.
Raw Material Defects

• Stereomicroscope analysis of a non-metallic inclusion initiated failure.
Raw Material Defects

• Scanning electron microscope analysis of a non-metallic inclusion initiated failure.

The non-metallic inclusion measured approximately 21 x 17 μm in size. Energy dispersive spectroscopy (EDS) was used to determine that the inclusion was mainly composed of Al and Ca oxides.
Raw Material Defects

- Check streak – loss of lubricant (tunneling) during wire drawing
Raw Material Defects

- Seam
Raw Material Defects

- Seam
Raw Material Defects

EDS elemental mapping of the fracture surface showing high concentration of foreign elements within the defect from wire drawing (Ca and Zn).
Raw Material Defects

- Longitudinal drawing defects – commercial quality wire