The Utilization of Advanced Metallographic Techniques to Verify In-service Damage in Long-seam Welded, High Energy Piping

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Long-seam Welded Piping

Issues

• Pipe manufactured with a longitudinally welded seam
• Mainly low alloy steel made to ASTM Specifications:
  – A 155 Classes 1 or 2
  – A 387 Grades 11,12, or 22
  – A 691 Classes 11,12, or 22
• Operating at temperatures above 950° F
Both thin-walled (hot reheat) and thick-walled (main steam leads and links) are a concern. Multiple in-service failures have occurred on each type of pipe: many additional pipe spools have been replaced. Fabricated elbows (e.g. clamshells) that have long seams have also failed.
Catastrophic failures have occurred by creep, more specifically “creep cavitation”.

Classic view of creep is by slow deformation of the component ending in final rupture:
- Visible deformation that permits detection and replacement.

Or a combination of creep and fatigue that is surface initiated (usually circumferential).
Failure Mode of LSW Pipe (cont.)

- LSW failures are catastrophic because the crack propagation is normal to the maximum stress direction (hoop stress)
- LSW failures occur with little visible deformation before rupture
- Cracking initiates subsurface
The mechanism of failure is creep cavitation

- Cavities initiate at discontinuities in the microstructure, i.e. inclusions, carbides
- Multiple initiation sites that are very localized at some microstructural feature such as grain size, weld fusion lines or weld centerlines
- Very little local deformation at crack location thus no global pipe deformation
Cavities grow slowly by a diffusion controlled mechanism

Cavity density and size increases until the cavities link-up and form microcracks

Microcracks growth at very rapid rate- rate dependent upon cavity density, local chemistry and local stresses
  – Little valid data of rate
  – Wide variation heat to heat
Failure Mechanisms for LSW Piping (cont.)

- The time from microcrack formation to final rupture can be very short (1-5 years) that lies within normal inspection intervals
- The prevention of pipe rupture depends upon detection of damage at the cavity stage
  - This presents are very large challenge for the NDE
Cavitation (creep voids) at the Cusp in a Double-vee Weld of a Hot Reheat Pipe

Magnification: 500X
Challenges for Non-destructive Inspection

- Cavities are very small (1-4 microns)
- Cavities are not surface connected or even interconnected until late in pipe life
- Cavities are intermixed with natural weld discontinuities
- Cavities are localized by weld geometry, but weld geometries are not uniform or consistent
Advanced Ultrasonic inspection using such techniques as time-of-flight-diffraction, focused, phased array have been successful in finding cavities.

Acoustic emission has shown promise.

Conventional UT with advanced design transducers is being developed.
NDE will find a suspect area

NDE can size flaw to some extent, but most NDE is not capable of characterizing flaw

NDE will lead to:
  – Run as-is
  – Replace
  – Perform metallurgical sampling/assessment
Metallurgical Assessment Options

- In-situ metallography (replication) – Very limited value as damage is not where inspection is possible
- Boat sampling – Typically from pipe OD – damage is not visible on OD till failure occurs
- Core sampling – Most useful for LSW
Core or Plug sampling examines entire cross section of weld, heat affected zones.

Allows examination of:
- Weld centerline
- Weld fusion line
- Fine-grained heat affected zone (type IV)
Plug Sample removed from a Hot Reheat Pipe
Typical Data from Core Sample

- Macro characterization of weld profile
  - Weld profile determines damage location
- Weld metal chemistry, including residuals that greatly impact creep life
- Microscopic examination
  - Type of post weld heat treatment
  - Presence of creep damage (cracking)
  - Weld quality level
Typical Data from Core Sample (cont.)

- Core sampling also gives an opportunity to perform a Cryo-crack examination.
- Core samples also allows the pipe to be examined for “peaking” or dimensional irregularity.
Typical double-vee Weld Preparation in a Hot Reheat Pipe
J-Groove Weld Preparation in a Link Pipe Section
Value of metallography is determined by the quality of the preparation
- Poor quality leads to false calls on the presence of cavities
- Minimum magnification of useful examination is 500X
- SEM aided Metallographic examination is preferred
Metallographic of a LSW showing Inclusions and Cavities

Magnification 1000 X
SEM image of a polished LSW cross-section—note scattered "cavities"

Magnification 1000 X
Scanning Electron Microscope view of a discontinuity (porosity) in a weld

Magnification 5000 X
Micro-cracking in a Cr-Mo Header caused by Creep Cavitation

Magnification 1000X
Cryocracking

- Sample preparation is complex
  - Location of notch is critical, notch determines plane of fracture
    - Damage can be missed if not precise
- If sample is fractured at too high a temperature fracture surface cannot be interpreted
Cavitation Damage on the Grain Boundaries of a Cr-Mo steel

Magnification: 5000X
Cavitation Damage in a Cr-Mo Pipe Sample as viewed using Back-scattered imaging in a SEM

Magnification: 1000X
Cavitation Damage in a Cr-Mo Pipe Sample as viewed using Back-scattered imaging in an SEM

Magnification: 1000X
Summary

- LSW piping is a serious issue - high probability of failure especially as this piping ages
- Many options for Inspection, UT, Advanced UT, AE
- NDE will lead to the need for metallurgical assessment