Liquid Metal Assisted Cracking-Liquid Metal Embrittlement in Rail

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What is Liquid Metal Assisted Cracking-Liquid Metal Embrittlement (LMAC-LME)?

- A component of metal under tensile stress.
- In contact with a liquid metal.
- The liquid metal will wet the grain boundaries and propagate a crack.

LMAC-LME in Resistance Spot Weld

LMAC-LME of Copper into Stainless Steel
Why Care about LMAC-LME?

- Grain boundary wetting with a second component can create a metallurgical notch.
- Localized toughness reductions.
- Localized ductility reduction.
- Cracks left unfilled by alloy resulting in mechanical notches.
- Notable recent incidents:
  - Germany, Fritz-Walter-Stadium in Kaiserslautern in 2005 due to LMAC
  - Galvanized power girders and yokes
  - Oil line due to environmental mercury
  - Resistance spot welds.
Where and Why Can LMAC-LME Occur in Rail

- **Liquid metal sources:**
  - Any braze, solder, or low-melting metal attachment onto rail
  - Trapped liquid metal in Flash Butt Welds where liquid metal (typically eutectic iron) is trapped in the joint
  - Tensile stress sources:
    - Neutral rail temperature (NRT) maintenance stress
      - Highest in areas with large thermal range
    - Rapid non-uniform heating or cooling strains
    - Residual stress.
Copper-based LMAC-LME in Rail

Copper Intrusion into Metal Apparent in Bond Wire Attachments (Note: martensite in base metal)

Copper on Crack Face Removed from Service
LMAC-LME Ultrasonic Inspection Indication from Web

Front Side of Exothermic Attachment Showing Extracted Face Side of the Crack (core removed from rail section for analysis)

Back Side Showing Copper Penetration into Steel
Copper-based LMAC-LME on Rail

Areas of Interest
Crack Growth Area

- Crack progresses from the surface into the web of the rail under loading cycles.
- Cracking path shows some plasticity evident in the growth.
- There is martensite present.
- These crack faces are decorated with copper.
- Copper extends beyond the martensitic region.
Examination of Microstructure

Closed and Open Cracks Decorated with Copper

Copper intrusion along grain boundaries
Copper-based LMAC-LME

- Copper penetration along grain boundaries.
- Cracks typically follow grain boundaries through the steel.
- These cracks can open up under cyclical loading.
- Non-equilibrium heating and NRT stress.
Flash butt welding diffuses carbon out of the solid into the liquid on the face.

The liquid can reach 2.7+% carbon.

If the flash face is not flat and pockets exist, eutectic iron can be trapped in the joint.

Ledeburite is cited as cause in many failure analyses.
Iron-Carbon Phase Diagram

- **Ledeburite**
  - Eutectic Iron Melting Point (cast iron), 1147°C

- **Rail Steel**
  - 0.75 to 1.1% C;
  - 1400°C +/- 50°C

Ledeburite in Flash Butt Weld Joint

Located Adjacent to Butt Line in Pocket or Pool Formed during the Process

Close up Showing the Dendritic Structure Typical of Eutectic Alloys
What Causes Ledeburite to Form?

- **Trapped liquid in the joint due to:**
  - Flash pits, according to literature, pool the higher carbon liquid on the flash face
  - Trapped liquid
  - Current concentration leading to preferential heavy flashing locations
  - Lack of acceleration according to patents filed in distant past.

- **Low upset levels insufficient to eliminate the flash pits.**

- **High carbon areas in the rail related to the terminal solidification of rail material and subsequent thermomechanical processing.**
AWS C1.1-66 suggests a minimum of 50% contact with the workpiece to minimize “hot spots”.

- Plant welders
  - typically grip and place the electrodes on the head and base near the flash interface of the rail producing a tight secondary loop.
- Portable welders have a much wider grip area.
  - higher inductance due to electrode configuration.
  - Transformer positioning can add inductance.
- Different secondary designs affect the efficiency of the secondary loop (inductance).
- The inductive loop in a loose secondary can store electrical energy that results in a dead short followed by a blow-out and arcing, voltage to current lag angles.
- Arcing, high voltage flash events, will lead to deep flash pits.
A large secondary loop is created by this arrangement with iron in the core of the loop (high inductance).

High inductive loads at lower voltage can create a lag condition during flashing.
- Dead shorts
- Large blow outs

Proper acceleration may heal or flatten these pits.
Summary

- **LMAC and LME can occur in rail:**
  - Tensile stresses and susceptible microstructures are present
  - Liquid metals can be found in common rail practices.

- **LMAC-LME often occurs with martensite and can be overlooked as a root cause of crack initiation.**

- **Process modifications can be made to minimize or mitigate LMAC and LME:**
  - Eliminate tensile stresses
  - Reduce or eliminate liquid metals.
Questions?
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