Copper-Induced Hot Cracking in Austenitic Stainless Steels

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Copper-Induced Hot Cracking:
- What is it?
- Metallurgical Mechanisms
- Manifestations
  - Copper (Cu) Abrasion
  - Dissimilar Welds

Failure Analysis Case Study:
- Incorrect filler metal used in an austenitic stainless steel pipe weld repair
- Metallographic analysis techniques
Copper-Induced Hot Cracking

- Copper-induced hot cracking is a form of welding related cracking whereby molten copper penetrates and weakens austenite grain boundaries ¹-³

- Cracking results from either Cu surface contamination of the base metal or by deposition of Cu-base filler metals on susceptible base metals ¹-³

- Copper colored veining along austenite grain boundaries in an as-polished sample easily identifies copper-induced hot cracking ²

Example of copper veining along austenite grain boundaries identifying hot cracking in a Fe-10.0Ni-24Cu weld deposit ⁴
Copper-Induced Hot Cracking, cont.

- Face-center-cubic (FCC) iron base alloys, like austenitic stainless steels, or those that experience an allotropic phase change to a FCC structure when heated, show high susceptibility to this form of cracking.

- Unlike typical forms of hot cracking, which occur in close proximity to the fusion boundary due to micro-segregation or constitutional liquation, copper-induced hot cracking can also originate away from the fusion boundary in the heat affected zone (HAZ) of base metal or reheated weld beads.

- Cracking morphologies are intergranular along austenite grain boundaries orientated perpendicular to the principle stress direction.

- Berdzs and Swartzbart showed that Cu-penetration depth is dependent upon temperature, austenite grain size, base metal composition, stress, and filler metal composition.
Liquid Metal Embrittlement (LME)

- Matthews and Savage attributed the intergranular failure and grain boundary penetration of copper-induced hot cracks to a phenomenon known as liquid metal embrittlement.\(^5\)

- LME reduces the fracture stress and ductility, of a solid metal when its surface under stress is exposed to a dissimilar metal in the liquid phase.\(^7,8\)

- According to Stoloff’s experimental observations, for LME to occur between a particular solid-liquid metal couple three conditions must be satisfied: \(^7\):
  1. A low mutual solubility between the liquid and solid must exist (compatibility)
  2. No intermetallic compounds may form at the liquid and solid interface
  3. A barrier to plastic flow exists in the base metal which is in contact with the liquid
Liquid Metal Embrittlement (LME)

- Schematic of the equilibrium condition between an austenite ($\gamma$) grain boundary and two equal interphase boundaries, $\gamma\gamma$ and $\gamma L$, under a stress ($\sigma$) \(^8\)

\[
\sigma_{\gamma\gamma} = \sigma_{\gamma L} \cos \left( \frac{\theta}{2} \right)
\]

- Smith states that a difference in metal interfacial energies promotes grain boundary wetting when the interfacial energy of the liquid phase is less than $\frac{1}{2}$ the grain boundary interfacial energy \(^8\)

- If this condition is satisfied, the dihedral angle ($\theta$), the wetting angle between a liquid when it meets two crystals, becomes zero the liquid can infiltrate and weaken the grain boundary by diffusion and capillary forces \(^8\)
Manifestations - CCC

Copper Abrasion – Copper-Contamination Cracking (CCC)

– During welding, Cu abraded to the work piece surface can melt
– The molten Cu attacks and weakens austenite grain boundaries cohesive forces and penetrates by means of LME\(^5\)
– This type of copper-induced hot cracking is known as Copper-Contamination Cracking, and typically occurs away from the fusion zone in the HAZ\(^3\)
– Cu fixturing, tooling, and contact tips have been identified as potential sources for abrading Cu to the base material\(^1\)
– Note, Cu that has been added as an alloying element does not promote CCC\(^5\)
– Numerous case studies of CCC indicate Cu fixturing to be the primary source; although, obscure instances of CCC, where the source of Cu is difficult to determine, exist\(^1, 9-11\)
Copper Abrasion – Copper-Contamination Cracking (CCC)

- Work by Mashula determined the susceptibility of CCC decreased with increasing temperature above a transition temperature in the weld HAZ, above the melting point of Cu\(^{12}\)
- It is theorized that this phenomenon is related to the dihedral angle’s response to temperature, which affects the wetability of austenite grain boundaries\(^8\)
- The response of the dihedral angle approaches near zero at the melting temperature of copper\(^{13}\)

\[\text{Dihedral angle of molten Cu on mild steel as a function temperature}^{13}\]
Dissimilar Welds

Dissimilar weldments made with Cu/Ni filler metal (70/30 wt%, respectively) or other Cu-base filler metals on austenitic stainless steels or structural steels have shown susceptibility to copper-induced hot cracking. Liquid Cu-base alloys, do not penetrate into the HAZ of a body-centered cubic base (BCC) structure.

Relative amount of 70/30 Cu-Ni filler metal penetration (backfilling) in HAZs of various base metal alloys.
Dissimilar Welds

- Cu atoms rapidly diffuse down the HAZ grains and decrease the austenite grain boundary cohesive strength, resulting in the formation of hot cracks in the presence of a strain field.\(^5\)
- After fissuring, the cracks are backfilled or “healed” to a degree by the superheated weld pool.\(^2, 5\)
- Given that the melting point of Cu is 1083°C, cracks can occur millimeters away from the fusion boundary.\(^1\)
- Due to steep arc welding thermal gradients, partial molten Cu-filler crack backfilling is possible and “unhealed portions of a crack may go undetected upon subsequent nondestructive testing.”\(^5\)
Copper-Induced Hot Cracking Failure Analysis Case Study
Copper Induced Hot-Cracking in an Austenitic Stainless Steel Pipe Weld

- NSWCCD was tasked to determine the cause of failure of a through wall weld metal crack found in a section lube oil piping
- Visual examination (up to 5x), metallography, and local semi-quantitative chemical measurement via energy dispersive spectroscopy (EDS) analysis techniques were performed
As-Receipt Inspection of Failed Component

The surface around Boss 1 was ground smooth, possibly to chase the crack/leak.

Significant amount of plastic deformation in the ground cracked region.
As-Receipt Inspection of Failed Component, cont.
Weld Marco Visual Examination

Specimens were electrolytically etched using a 10% oxalic solution

Multiple repair welds and welding defects, such as burn through and cracking, are evident in the Boss 1 interior weld
Under closer magnification it was clear that the weld metal grain boundaries and darkly etched region appeared “dugout” by the chemical etch.
Local Weld Metal EDS Chemical Analysis

Electron Back Scatter Image of Metallographic Sample A

EDS Location 1
CuNi Weld Metal

EDS Location 2
Cu Diluted Austenitic Stainless Steel Weld Metal

EDS Location 3
Austenitic Stainless Steel Base Metal
Local Weld Metal EDS Chemical Analysis

Boss 1 Sample A – As-Polished

Cu Decorating Grain Boundaries

EDS Map of Elemental Cu

Cu Rich

200μm

40μm
Metallurgical and chemical evidence revealed high volumetric and elemental percentages of Cu in the austenitic stainless steel weld metal surrounding the cracks.

- Cu was not found in weld metal away from cracking.
- Cracked areas containing Cu were associated with a series of repair welds.
- The large amount of plastic deformation around the cracked areas appears to have been caused by excessive heating associated with multiple weld repairs.
- The high residual stresses induced by the multiple weld repairs would have significantly added to the stress needed to cause cracking.
- An incorrect copper-based filler metal used during one of the weld repairs appears to be the source of contamination causing cracking.
References


Questions