TROUBLESHOOTING CRACKS IN STEEL CASTINGS

By Rodman Duncan
Casteel Technical Service
rod@casteeltec.com
360 468-3588
This presentation is given to the members of Steel Founder’s Society of America in order to serve as a framework which can be used to identify the cause of cracks in steel castings and determine the appropriate corrective action.
The First Step in the Crack Troubleshooting Process is to Identify:

- Where do cracks occur?
- When do cracks occur?
Where do cracks occur?

At a hot spot in the castings (ingate, hot riser, heavy section)
Under a riser, on the riser contact surface
Heavy section (greater than 6” inscribed sphere)
At a stress-raiser on a casting surface (small radii, change of section)
Inside a cored surface
Adjacent to an ingate
Adjacent to a chill
When do Cracks Occur?

During solidification and cooling (visible after shakeout & blast)
During processing (grinding, arc air, welding)
After heat-treatment (especially Q&T)
Many days after Q&T (“delayed cracking”)
Definition: “Crack Morphology”

The appearance, pattern and structure of a crack on the casting surface, the open crack face, or in cross-sectional view
Index of Crack Types

(1) Hot Tears
(2) Hot Cracks
  (2a) Ingate Crack
  (2b) Bore Crack
  (2c) Chill Crack
(3) Stress Cracks
(4) Riser Cracks
(5) Aluminum Nitride Crack
(6) Quench Crack
(7) Hydrogen Crack
(8) Craze Crack
(1) HOT TEARS

The crack is in a hot spot, near an ingate or riser, or a heavy section; and it is very visible after shakeout
The jagged and discontinuous surface appearance of a hot tear on the surface
Hot-Tear

Crack Morphology:

- **Surface**: Wide and discontinuous (jagged)
- **Face**: Very dark (oxidized) and featuring dendritic regions
- **X-section**: darkly oxidized, deep, wide, discontinuous, lined with silicates

- Crack face often dendritic for a hot tear.
- Crack face often oxidized (prior to a heat treatment)
Cross Section of Hot Tear

Machined Outer Diameter

liquid penetrant indications
Hot-Tear Causes

1. Hindered contraction during the latter stages of solidification
   - Casting/rigging design features: opposing flanges or appendages, gating system runners

2. Hot spot or large thermal gradient
   - Isolated heavy section, or heat concentration at an ingate or riser contact

3. Constriction stress caused by mold or core
   - Excess mold/core strength or sand density

4. Low melt-point phases in the inter-dendritic regions
   - Usually due to high sulfur, or type II sulfide inclusions
   - High pouring temperatures
Hot-Tear Cures

1. Identify source of stress and eliminate it:
   • Stress is in a direction across the direction of the tear
   • Change runner configuration

2. Reduce mold/core constriction
   • Ram-up lightner pockets in mold, hollow our core, provide core mandrel, etc
   • Reduce binder level
   • Reduce sand compaction

3. Reduce hot spot
   • Change ingate location
   • Use multiple ingates
   • Lower pouring temperature
   • Provide chill

4. Reduce sulfur level to < .02%
   • Eliminate type II sulfides (increase deoxidation)
(2) HOT CRACKS

The crack is a tight, slightly jagged, and shallow crack at a hot spot, at a radius or at a section change or junction. It may or may not be visible at shakeout (may need MPT).
Hot Crack

Crack Morphology:

• Surface: much tighter than a hot-tear, slightly jagged, sometimes under a vein

• Crack face: small, shallow regions of dark inter-dendritic fracture at crack origin

• X-section: discontinuous & dendritic, crack lined with silicates and dark oxide, possibly also type II sulfides
X-section at 100X of Hot Crack showing discontinuous path and oxide coatings
Hot Crack showing dendritic fracture face in cross section and dark oxidized region on open crack face
HOT CRACK LINED WITH OXIDATION PRODUCTS
Hot Crack Causes

1. Casting design feature such as small radii, section junctions
   • causing localized delayed solidification and stress
2. Localized hot spots at ingates and riser contacts
   • large thermal gradients during solidification
3. Loss of mold support during very late stage of solidification
   • Sand binder burn-out in no-bake binders
4. Type II sulfides at S > .02%
5. High pouring temperatures
Hot-Crack Cures

1. Follow casting design rules:
   • Larger radii, tapered junction between sections
2. Provide localized cooling:
   • Cracking brackets (cooling fins) across crack
   • Chilling sand or chilling coating in radii (chromite, zircon)
3. Provide mold support to heavy/hot section (very large castings only)
4. Reduce pouring temperature
5. Eliminate veining (Fe3O4 additive)
6. Eliminate type II sulfides
   • Increase deoxidizers
(2a) Ingate Hot Crack

- Located adjacent to an ingate
- Morphology same as “stress crack” or “hot crack”
- Worst case appears as ‘hot tear’
Ingate Crack Causes

1. Extreme hot spot at ingate
2. Ingate modulus too large
Ingate Crack Cures

1. Reduce modulus of ingate
   • Decrease the V/SA ratio (knife gate)
2. Increase the number of ingates
(2b) Bore Crack

- The crack is inside of a cylindrical cored surface, parallel to axis of core

- Usually has morphology features as described under “hot crack”, or “stress crack”
Bore-crack causes

1. Core constraint
   - High hot-strength (binder%)
   - Solid core

2. Hot spot near riser or ingate

3. Stress riser on cored surface
1. Reduce binder %
   • Sand tensile about 75 psi (the lower the better)
2. Hollow out core, or use “lightner” blocks or mandrel
3. Chill hot spot
   • use chill sands, or steel chill
4. Put cracking brackets in core
(2c) Chill Crack

- Located always under or adjacent to a chill
- Morphology same as “stress crack” or “hot crack”
Causes and Cures of Chill Crack

1. If located under a chill, reduce chill thickness
2. If located adjacent to a chill, taper the edges of the chill at 30°
(3) COLD STRESS CRACK

The crack is at a radius or at a section change or junction, or other stress-raiser, is very tight, may be visible or not after shakeout.
Cold Stress Crack

Crack Morphology

- **Surface**: The crack is very tight and continuous, often visible only after MPT

- **Crack Face**: shiny, no dark areas, intergranular, fine grained fracture

- **X-section**: The crack is continuous, not dendritic, no oxides or silicates
CRYSTALLINE FACE OF STRESS CRACK ALONG EMBRITTLED FERRITE GRAIN BOUNDARIES
STRESS CRACK SHOWING SLIGHT OXIDATION
STRESS CRACK AFTER HEAT-TREAT
STRESS CRACK ADJACENT TO LINE OF INCLUSIONS

Top view of section sent for examination. A surface indication was detected by magnetic particle. Microstructure of Crack in Section. Entrained reoxidation products caused the fracture during HT.
Stress Crack Causes

1. Stress during cooling
   - Hot shakeout, fast cooling, rough handling
2. For alloys CE>.6, long delay from shakeout to normalize
3. Hot spots in casting, thermal gradients
4. Sub-surface flaws
   - Inclusions, shrinkage (in radii)
5. Casting stress-raisers, sharp radii
Stress Crack Cures

1. Cooling fins or chill sands
2. Reduce stress-raisers, apply casting design rules for radii and section change
3. Longer shakeout times
4. Normalize quickly after shakeout
5. Reduce thermal gradient, multiple ingates
6. Reduce alloy CE
(4) RISER-CONTACT CRACKS

The crack is in a riser contact surface
Riser-Contact Crack

- Crack Morphology:
- Surface: Cracks are either jagged, or straight across riser, or straight cracks radiating out from center of riser (star crack)

- Crack Face: shiny or grey, fine intergranular

- X-section: straight, intergranular, continuous, deep, may be oxidized or not
DEEP RISER CRACK DURING QUENCH SHOWS TINTING FROM TEMPER
EXTENSIVE CRACKING MAY BE DUE TO SEGREGATION

Under riser quench cracks
Severe riser cracking can be caused by sub-surface secondary shrinkage.

(A) Under riser cracks. (A) as-received surface, (B) surface after 0.35” depth removed.
PARALLEL RISER CONTACT CACKS CAUSED BY ARC-AIR AND SEGREGATION
Riser-contact Crack Causes

1. Inadequate preheat during arc-air
   • Especially if alloy CE > .6
2. Under-riser C and Mn segregation extending into casting
   • Particularly in the case of a “star crack”
3. Secondary shrink under contact
4. Coarse & brittle as-cast microstructure
5. Grinding cracks normal to grind direction
6. Quench crack
   • Occurs only after Q&T heat-treatment
Riser-contact Crack Cures

1. Preheat to 250F minimum before arc-air when CE > .6

2. Reduce segregation & secondary shrink:
   • Use mildly-exothermic hot-topping, 10 to 20% D riser thick
   • D neck > .6 D riser
   • Riser H/D > 1.5

3. Normalize @1750F prior to torch cut @ arc-air

4. Follow guidelines for proper quenching
(5) ALUMINUM-NITRIDE CRACKS

The crack is in a heavy section, or on a heavy section riser contact, and is visible as-cast, and is a “meandering” grain boundary crack.
The AlN crack (A) typically outlines the large prior-austenite grain boundaries, but may not be as continuous as this example shows. The “rock candy” feature of the crack face (B) is very indicative of this type of crack.

• (A)  • (B)
Aluminum-Nitride
“rock candy” Crack

Crack Morphology:
Surface: Al-N cracks have a distinctive meandering path with small curved features, some with branches
Crack face: The classic “rock candy” fracture
- smooth large grained facets, often more severe near the casting surface
- Usually a deep crack
- Lightly colored, no dark regions
The two lower microphotos are taken by an SEM on a fracture face facet, and show a distinct cross-hatched morphology caused by the precipitate of AlN.

Macro-photograph of section following a macro-etch in a solution of 50% HCL - 50% water at 50C. (ASTM A703) Grain boundary delineation (arrows) that is consistent with aluminum nitride embrittlement. 2.2X.
Macro-photographs of “Rock Candy” Steel Fracture Surfaces. Montage of Button from Back of Fracture Surface Following Macrotetch in Solution of 50% HCl, 50% Water at Approximately 50°C.
Aluminum-nitride Crack Causes

1. Usually caused by brittle precipitate of aluminum nitride at prior austenite grain boundaries.

2. Aluminum nitride is a result of:
   - High residual aluminum
   - High residual nitrogen
   - Slow cooling in heavy sections

3. Shallow surface Al-N cracks in very heavy section caused by diffusion of N from PUN binder
Cures for Al-N cracks

1. Reduce N in arc furnace by C boil of .30 C minimum for N less than 80 ppm
2. Control residual Al to .025 to .04%
3. In very heavy section, replace Al deoxidation with Ca
4. Additions of N stabilizers Ti or Zr
5. Shakeout very heavy section parts above 2400F and allow to air cool
6. Al-N cannot be eliminated by heat treat
(6) QUENCH CRACKS

The crack is a sharp, straight crack that is visible after Q&T heat-treatment
A sharply defined quench crack in a section removed from a casting
Quench Crack

Crack Morphology:
Surface: a straight sharp crack with no branching
Crack face: most of the crack face will be a fine transgranular surface with a light tan or blue heat tint. The perimeter of the crack will have a curved edge.
Inspect the crack face for chevrons that indicate crack origin. Inspect origin for pre-existing flaw or crack. This region will be dark grey to black in color.
The crack goes straight through several sections of different thicknesses
The quench crack from the previous slide opened up to reveal the crack face. (A) darker oxidation from a surface crack that had previously existed  (B) a region of internal shrinkage
Quench cracks. (A) as-received surface, (B) surface after 0.50” depth removed
Quench Crack Causes

1. Pre-existing surface flaw (at crack origin)
   • Surface shrink, hot crack, stress crack, etc.
2. Sub-surface shrink
3. Hardenability too high for section size
4. Non-uniform quench due to poor agitation, hot water, or loading conditions
5. Casting quenched too cold, or not tempered soon enough after quench
Quench Crack Cures

1. Keep alloy C\(<\.3\) and CE \(<\.6\)
2. Inspect part prior to quench for pre-existing flaws, repair before quench
3. Control water quench:
   • Quench from 1600/1650F
   • Water \(<100F\), water velocity \(>50\) fpm, 1 gallon water per lb of castings
   • Remove high-CE parts at 300/400F and air cool
   • Provide spacing and even loading on tray
4. Temper soon after quench
5. Reduce riser segregation
(7) HYDROGEN ASSISTED CRACKING
The crack is in a heavy-section, and occurs several days to weeks after the final heat-treatment.
“Delayed” Hydrogen Assisted Cracking (HAC)

Crack Morphology:
Surface: Crack is straight, slightly jagged, in heavy section (looks similar to quench crack)
Crack face: Crack origin is at a “flake” at center of heavy section, sometimes in shrink zone. Crack face covers entire section, coming to surface in a few locations. Crack surface has distinct pinnacle and dimple features (“Hydrogen fish-eyes”)
The crack face can have different morphology, but the fracture always proceeds from the center to the outside of the section.
MULTIPLE INTERNAL CRACKS ARE “HYDROGEN BURSTS”
Macrophotograph of Cracked Steel Casting Section. Hydrogen was the suspected cause
Cause of HAC

1. HAC worse in high strength steels
   • Also worse at higher Nickel levels (>2%)

2. H above about 5ppm in steel before casting
   • H pickup in liquid steel from moisture in refractories, alloys, mold, atmosphere, etc.
Cures for HAC

- Reduce hydrogen in liquid steel
- Vigorous boil in arc furnace > 0.3% C, H < 2 ppm
  - Induction furnace can have high H > 6 ppm
  - AOD has least H < 1 ppm
- Eliminate all sources of moisture in refractories, alloys, mold coatings
  - Minimize atmospheric exposure, turbulence
  - Skin dry a green-sand mold

1. Vent board ladles
   - First heat on boards has high H
2. Lighten out heavy cast sections
3. Provide H diffusion cycle: > 24 hrs @ 500F
(8) CRAZE CRACKING

The surface shows a craze-crack network of fine, shallow cracks which can be seen in the as-cast surface, usually with MPT.
Craze Cracking

Crack Morphology

Surface: A fine and indistinct network pattern of cracking, usually visible only with MPT, (looks like a pottery glaze crack)

Crack face: usually the crack is too shallow to open up

X-section: Very shallow crack, through ferrite or oxide at prior austenite grain boundary, highly oxidized
Causes of Craze Cracking

1. In green sand molds, due to high-temperature oxidation at prior-austenite grain boundaries
2. Excessively high shakeout temperatures above 2000F
   • Can be caused by combustion of binder and sand falling away from cast surface
3. Oxidation damage at austenite grains due to excessive austenitizing time and/or temperature
4. In very heavy sections, due to surface nitriding from PUN binder
Cures for Craze Cracks

1. In green sand mold, reduce moisture or skin-dry mold surface
2. In PUN, increase Fe3O4 addition to 5%
3. Reportedly worse at low levels of C, increase C to .25%
4. Reportedly worse in steels with high Ni
5. Usually can be removed by light grinding
A series of papers on cracking in steel castings were presented at the 1998 T&O Conference and published in the “Proceedings of the T&O Conference” from that year.

These papers should provide further information regarding causes and cures of cracks in steel castings.