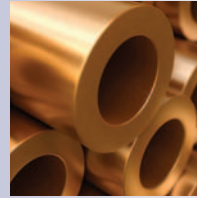
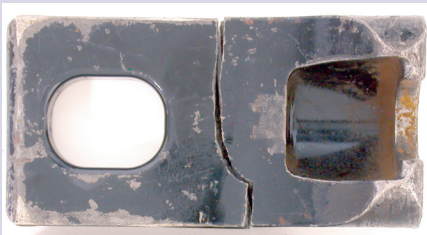


Metallurgical Minutes



Materials Testing and Engineering • Failure Analysis • Manufacturing Problem Solving • Litigation Support



Characteristics of Brittle Fracture

- Brittle fractures don't exhibit permanent plastic deformation such as bending, twisting or stretching. Often the two halves of the fracture can be fit back together like interlocking puzzle pieces as shown above.
- The fracture surface is usually approximately perpendicular to the direction of the tensile stress that caused the fracture although compound stresses exerted from multiple directions may result in variations.
- The fracture surface morphology often, but not always, exhibits a "flow pattern" that leads back to the point of fracture initiation. In the brittle fracture example shown below, the fracture initiated from an internal defect and propagated outward from there.



continued on next page

Brittle Fracture

Elasticity, Toughness and Liberty Ships

Whenever a force is applied to an object, that object deforms. That seems pretty obvious since we've all seen the process in action. However, that deformation also occurs on microscopic or even atomic levels that we can't see and, from an engineering perspective, these "invisible" changes are extremely significant.

If the object returns, or "springs back", to its original shape when the force is removed, the deformation is **elastic**. If the deformation remains and is permanent when the force is removed, the deformation is **plastic**.

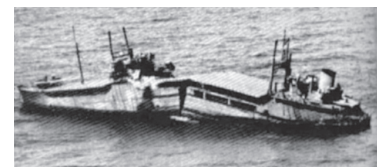
Fractures that plastically deform – bend, twist, stretch, etc, - are classified as **ductile** fractures.

Fractures that don't exhibit plastic deformation – often the two halves can be fit back together like puzzle pieces – are classified as **brittle** fractures.

"Brittle" brings to mind materials that have little or no flexibility or strength and fracture easily. These characteristics, however, are more accurately described as **embrittlement**, a subtle but important difference. Embrittlement in metals results from defects or degradation that occur in production or in service such as defective heat treatment, hydrogen absorption, and exposure to specific chemical environments or molten metals.

While embrittled metals fail by brittle fracture, perfectly sound metal can also fail by brittle fractures resulting from:

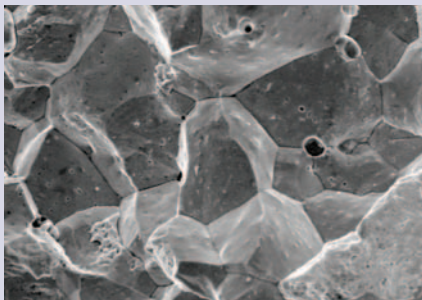
1. Design errors.
2. Poor materials selection.
3. Improper or defective manufacturing processing.
4. Abuse.
5. The service environment.



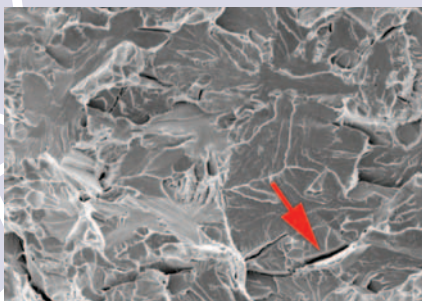
continued on next page

continued from page 1

- The microstructure of steel (and virtually all industrial metals) is composed of microscopic interlocking crystals, or grains. When examined at high magnification using a scanning electron microscope, brittle fractures are either intergranular or transgranular. Using a brick wall as a metaphor, this is equivalent to fracture of the wall between the bricks (intergranular), or fracture through the bricks (transgranular).



Intergranular brittle fracture in steel magnified 1000 times using a scanning electron microscope (SEM). In this fracture mode the individual interlocking crystals, or grains, that make up the microscopic structure of the metal are apparent and separation, or fracture, occurred at the interfacing facets of the grains.



Transgranular brittle fracture in steel magnified 1000 times using SEM. In this type of brittle fracture, the fracture propagates through the grains, exposing an individual fracture surface on each grain. The boundaries, or interface, at the facets where the interlocking grains meet is visible at several locations, with a typical example indicated by the arrow.

Brittle fractures are extremely dangerous. Here we are talking about single cycle overload fractures, the complete fracture of a component or assembly that happens with the application of a single load. Because there is no visible deformation, as is exhibited by ductile fractures before failure, brittle fractures occur without warning. Unlike ductile fractures, brittle fractures propagate, or grow, very quickly once they initiate. Brittle fracture growth at or above the speed of sound (1125 feet per second) is not uncommon. The result can be catastrophic.

In dealing with industrial metals – and steel in particular – variations in alloying elements, production of the bar, plate or sheet at the mill, and processing used in product manufacturing result in a wide range of properties. These properties include hardness, strength, toughness, elasticity, ductility, and the ductile to brittle transition temperature (DBTT).

Carbon and low alloy steels can be modified by heat treating, welding, and other manufacturing processes to shatter like glass or flex like a spring. The DBTT can result in one steel having both properties, but at different times, depending on the temperature it is exposed to. In this phenomena, normally ductile and elastic steel becomes extremely brittle below a specific temperature. That temperature varies widely depending on the type of steel and its processing. Ideally, the DBTT should be so low (well below 0° Fahrenheit) that exposure to that temperature would be highly unlikely. In “worst case” scenarios, however, the DBTT can be well within normal ambient temperatures or even higher.

The classic example of brittle fracture due to the affects of the DBTT is illustrated by what happened to a class of cargo ships called “Liberty Ships”. Early in World War II, Britain desperately needed American food and supplies; supplies that had to be transported by ship. Unfortunately, German U-Boats were sinking cargo ships at three times the rate at which they could be replaced using existing ship building methods. Ship builders responded with the revolutionary Liberty Ship design, cargo vessels made from cheaper more widely available steel, and constructed quickly by welding rather than traditional time consuming riveted construction. Construction times dropped from nearly 300 days to under 50 days. There was one problem though. The ships had tendency to crack, and in some cases break completely in half, in cold weather.

Welding, in place of riveted construction, was a novelty in ship building at the time and was initially blamed for the failures. Intensive analysis, however, eventually identified the relatively high DBTT of the steel used for these ships as the root cause. The cold water temperatures of the North Atlantic transformed the normally ductile steel into an extremely brittle material, and single load events ranging from large waves at sea to heavy cargo load placement were sufficient to cause brittle single cycle fractures.

Brittle single cycle overload DBTT fractures can occur when a number of conditions are present. First of these is a steel which has a relatively high DBTT. This is extremely difficult to predict, although Charpy Impact testing at a range of temperatures provides a useful estimation. Second is a feature, or design configuration, that can act as a focal point for stress (stress riser) such as a notch, sharp corner or even microscopic cracks resulting from manufacturing or service. The third condition is a load or stress of the required magnitude which, as we have noted, can be quite low.

As with most failures, there were other contributing factors to the Liberty ship brittle fractures. The welding, which is now accepted practice in ship construction, was performed by newly trained welders since much of America’s experienced

continued on page 5

Brittle Fractures Case Studies

The Boston Molasses Disaster sounds like an urban legend but it actually happened. On January 15th, 1919 a storage tank, 50 feet tall and 90 feet wide, burst in north Boston. The tank contained over 2 million gallons of molasses. The pressure wave alone threw trucks into Boston harbor and large pieces of the tank destroyed nearby buildings and an elevated train overpass. This was followed within seconds by a tidal wave of molasses between 8 and 15 feet high moving at 35 miles per hour, and exerting a pressure of 2 tons/ft². The wave demolished houses and office buildings, lifting others from their foundations. Twenty-one people died and over 150 were injured.



Since no one expected the catastrophic failure that resulted in the Boston Molasses Disaster, photos of the actual storage tank are difficult to confirm. This image, however, appears to be from the appropriate time frame and the dimensions of the tank in the background are consistent with the failed tank.



Destruction of the elevated train overpass after impact by sections of the storage tank and the tidal wave of molasses that followed. Although not confirmed, the twisted piece of riveted metal plates at the right may be part of the tank.

The tank was made from riveted cast iron plates. The “engineer” who designed it had no formal training and no testing was done before it was put into service. The instantaneous and explosive nature of the failure points strongly to brittle fracture as the mode of failure. However, the limited available knowledge of failure analysis at the time resulted in multiple theories as to the root cause, which has not been conclusively resolved to this day. These include insufficient strength due to poor design, pressure build up in the tank due to fermentation of the molasses, and overload resulting from the DBTT of the cast iron plates.



The destruction of buildings from the Boston Molasses Disaster was reminiscent, on a more localized scale, of scenes from the recently concluded First World War.

Brittle Fracture

Boston

Brittle Fracture



Unlike the Boston molasses tank disaster, the Hoan Bridge failure had the advantage of occurring at a time when sophisticated analytical and investigative technology was available. As a result of the advanced inspection capability of this technology, the “Hoan Bridge Disaster” never occurred, but it was close.

A simple, but elegant design, the Hoan Bridge spans the Milwaukee harbor front on a north-south axis, carrying two traffic lanes and a breakdown lane in each direction. Its location exposes it broadside to Lake Michigan on the east side of the structure and inland Wisconsin on the west, a factor that may have had a contributing affect to the failure.

Routine inspections identified cracking at several locations in the girder webs of the support spans. These were deemed non-critical and monitored closely with limits set on allowable traffic while a comprehensive repair plan was developed. On December 13th, 2000, before repairs could be implemented, a 217 foot section of the bridge began to sag as a major brittle crack rapidly propagated through one of the girders.



Small, previously monitored brittle cracks in the Hoan Bridge support span girder webs rapidly propagated on a cold December morning during a period of heavy vehicle traffic.

Subsequent analysis identified an unusually high degree of constraint to normal expansion and contraction, and a geometric stress riser, at weld intersections of the fabricated span. A combination of extremely cold weather, heavy vehicle traffic, and the temperature gradient between the lake and inland side of the structure may all have added their cumulative affects.

workforce had been drafted into the military. As a result, many of the welds contained small crack-like flaws that acted as stress risers from which brittle cracks could easily initiate. This led to the mistaken initial belief that the welds were the root cause of the failures. Other brittle cracks initiated at square hatch openings which had sharp corners with very little radius, a local stress concentration introduced by either poor design or production schedule pressures that left no time for “details” like well finished corner radii.

The cheaper, and more widely available, steel used in Liberty ship construction had poor toughness characteristics. Toughness is generally defined as a materials resistance to crack growth. This deficiency was dramatically amplified by the steels high DBTT. Riveted construction with this material may have been adequate, since the brittle crack growth would have terminated at the end of each individual riveted plate. The welded structure of the Liberty ships, however, essentially made them into the equivalent of a single piece of steel, and once a crack initiated there was no interruption in the continuity of the structure to stop crack propagation. As a result, some cracks traversed the entire hull structure virtually instantaneously. Fifty years of welded ship construction, with steel of appropriate quality, has vindicated this form of fabrication.

Brittle single cycle overload fractures resulting from high DBTT are only one of many root causes of this fracture type. Others include:

Excessive loading beyond the load carrying capacity of the material. This rather obvious cause can result from a variety of conditions including undersized components in the initial design, abusive overloading by the end user, and lubrication failures or inadequacies that generate high loads through friction or seizure.

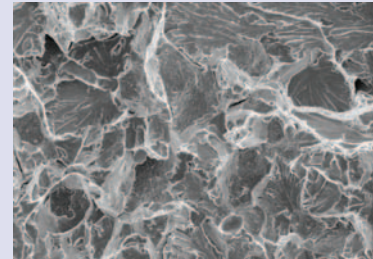
Exposure to a detrimental temperature range during heat treating or in service. These temperatures vary with specific steel type and include Blue Brittleness (450° F - 700°F), Temper Embrittlement (700 - 1070°F), Sigma Phase Embrittlement (1050 - 1800°F) and many others.

Neutron embrittlement, a concern in the nuclear power industry that raises the DBTT as a result of prolonged irradiation.

In some respects the study of brittle fracture and the broader study of fracture mechanics evolved from being a curiosity, into an engineering branch of learning as a result of the crucial need to identify the root cause of the Liberty ship failures. The study of brittle fracture on the microstructural and atomic levels is an extremely complex and on-going endeavor and this discussion deals with only a brief overview of the practical rather than the theoretical aspects.

IN THE WORKS...

We're often asked "What do you do?" If we hesitate to answer, it's because the variety of materials, components, and testing challenges is almost unlimited. A few of our recently completed analyses include:



MAI service life analysis of a municipal electric power utility's generator rotor, included evaluation of the DBTT by Charpy Impact testing at a range of temperatures. Our conclusions were used to plan cost saving maintenance programs.



Analysis of a failed plate heat exchanger used in a pharmaceutical processing plant. Our evaluation determined that the failure was caused by degradation of attached components, rather than any deficiency in our client's plate heat exchanger.



Our investigation of failed power transmission take-off shafts revealed fundamental processing defects in heat treating that were easily and inexpensively resolved.

Brittle Fractures Case Studies

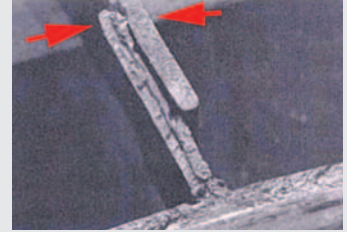
On March 15th, 1979 the oil tanker MV Kurdistan broke in half off the eastern coast of Canada releasing thousands of gallons of oil into the sea. Although the result was similar to the Liberty ship failures, the root cause was different. By this point in the progress of ship building technology, welded construction was the norm.



Despite breaking completely in two at sea, the MV Kurdistan miraculously made it back to port. Or at least half of it did. The bow section sank shortly after the sequential failure of the keel, hull plates and deck.

The estimated temperature of the oil on board was approximately 140° F, apparently due to extraction processing just prior to loading. The air temperature was 32° F and the water temperature was not much higher. Thermal stresses from of this temperature differential resulted in high tensile stresses on the hull and bilge keel structures.

The Kurdistan was designed to withstand these stresses, but not the weld defects present in the bilge keel resulting from a flawed repair two years earlier. Lack of weld penetration at this butt joint produced a stress riser which initiated a brittle fracture. Once initiated, the thermal driven tensile stresses and rough seas contributed to rapid fracture propagation through the hull and deck plates and breakup of the ship.



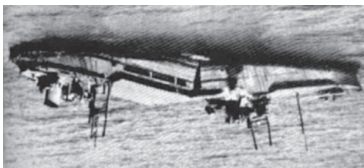
Failure initiation site at the bilge keel weld. This weld only partially penetrated the adjoining plates in this butt weld configuration. Additional welds, that were specified, were never made. Frigid sea water plunged into the cargo holds exposing many parts of the structure to temperatures below their DBTT, but this was a secondary affect. The brittle fracture had already initiated and spread.

Brittle Fracture **Canada**

Metallurgical Associates Inc. is an independent materials testing and engineering facility accredited by the American Association for Laboratory Accreditation (A2LA-ISO/IEC 17025). Our expertise includes failure analysis, process problem solving and process/material certification and selection. For a quote or discussion of your analytical requirements, contact Tom Tefelske (tomt@metassoc.com), Dan Kiedrowski (dank@metassoc.com) or Rob Hutchinson (robh@metassoc.com), or call (262) 798-8098 or Toll Free (800) 798-4966. Visit MAI's web site at www.metassoc.com.

BRITTLE FRACTURE

IN THIS ISSUE



PRSR STD
US Postage
PAID
Milwaukee, WI
Permit No. 1275



2325-B Parklawn Drive
Waukesha, WI 53186
262-798-8098 • Fax 262-798-8099
Toll Free 800-798-4966
E-Mail: info@metassoc.com
Web Site: www.metassoc.com

MAI
METALLURGICAL
ASSOCIATES, INC.