The Maine Maritime Steel Phase Apparatus – a New Design for Materials Lab Courses

Steel Metallurgy and Strength of Shipbuilding Materials

J. Schoof and P. Wlodkowski
Maine Maritime Academy, October 18, 2014
for Maritime Education Summit

What is today's talk about?

1. Why we are interested in steel metallurgy and strength of shipbuilding materials
   - Crack fractures in cold water
   - High temperatures changes to steel
   - Three ships whose hulls failed from brittle cracks in steel

2. Three lab tests of steel strength in our materials lab course
   - Tensile strength- at room temperature
   - Impact strength – brittle point at low temperatures
   - Heat treat – crystal changes in steel and predictable effects (focus of this paper)

3. The Maine Maritime Steel Phase Apparatus – a very useful demo tool
   - For steel phases and their effects
   - Design and construction
   - Lab exercises

"Broken Ships"

Three Ships That Failed From Brittle Steel

Why we are interested in steel metallurgy and strength of shipbuilding materials

- The Schenectady – and more than 1000 Liberty ships
- The Majestic
- The Titanic

The Schenectady

- 2580 Liberty ships, 414 Victory ships and 530 T2 tankers built 1941-1946
- The Schenectady was the first catastrophic failure – but not the last!
- 1031 damages due to brittle fracture reported by April 1946
- More than 200 Liberty Ships were sunk or damaged beyond repair
- Only two are still afloat

The Schenectady

Cargo vessel (DWT 11000 Liberty Ship) (T-2 tanker)

- 152m long T2 tanker 'Schenectady'
- January 1943
- In the builder's yard in Portland, Oregon
- A few days after completing sea trials
- While lying at the outfitting dock
- Suddenly broke in two

- Conditions:
  - water temperature 4°C
  - no waves / calm
  - air temperature -3°C
  - winds light

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5

The Schenectady

Cargo vessel (DWT 11000 Liberty Ship) (T-2 tanker)

- Failure was sudden - loud bang heard a mile away
- Fracture extended through the deck, the sides of the hull, the longitudinal bulkheads and the bottom girders
- The vessel jack-knifed, hinging on the intact bottom plate
- The central part of the ship rose clear of the water so no flooding of the hull through the fracture occurred

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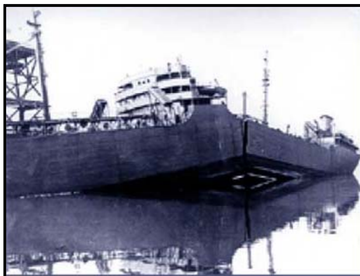
6



The Schenectady – the cause

The report concluded cause was

- Defective weld under stress created a brittle crack fracture

The Schenectady – the cause

- Early Liberty ships were lost to crack damage, particularly in cold North Atlantic waters
  - By 1946, 1441 cases of damage had been reported for 970 cargo vessels - 1031 were Liberty Ships
  - In T2 tankers 50% of fractures began in welds
  - Parker reported that of 1289 Liberty Ships, 233 were sunk or incurred serious damage
  - Twelve ships broke in half without warning, including the SS *John P. Gaines*, which sank in 1943 with the loss of 10 lives

The Schenectady – the cause

- Constance Tipper of Cambridge University discovered the cause in 1962
- She showed that the fractures were caused by the grade of steel, not by welding
- She discovered that the ships in the North Atlantic were exposed to temperatures that could fall below a critical point when the mechanism of failure changed from ductile to brittle
- The hull could fracture easily


THE BRITTLE FRACTURE STORY

CAMBRIDGE

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The Schenectady – the cause

- Welded (as opposed to riveted) hull construction allowed cracks to run for large distances unimpeded
- A common type of crack began at the square corner of a hatch which coincided with a welded seam, both the corner and the weld acting as stress concentrators
- Also - the ships were frequently grossly overloaded and some of the problems occurred during or after severe storms at sea

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10

The Schenectady – solutions

- Various reinforcements were made to the Liberty ships to arrest the crack problems
- The next design, the Victory ship, was stronger and less stiff to better deal with fatigue cracks
- Changes were made to the steel itself
  - Different steel alloy
  - Different manufacturing processes
    - grain size of steel
    - deoxidation methods
    - heat treatments

The Schenectady – lessons learned

- The failure of the Schenectady and other war-time ships led to study of brittle fracture in hulls
- Temperature affects material toughness (brittleness)
- The right steel is critical for welded ships – especially in the cold North Atlantic and Southern Oceans

Ship #2: The Majestic

- Launched 1914 – White Star Line
- Until 1935 the largest ship in the world
- 1928 – additional passenger elevator was added
  - New, square hole in the deck
  - Stresses concentrated at the sharp corner
- Stresses drove a crack across the deck and down the side of the ship
- The crack struck a round porthole and stopped
- 3000 lives would have been lost in the Atlantic between New York and Southhampton

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13

- On 14 April 1912, at 11:40 p.m., Greenland Time, the Royal Mail Ship Titanic on its maiden voyage was proceeding westward at 21.5 knots (40 km/h)
- Lookouts sighted a 150,000 to 300,000 ton iceberg 500 m ahead. Immediately, the ship's engines were reversed and the ship was turned to port
- In about 40 seconds, the ship struck the iceberg below the waterline on its starboard (right) side near the bow.
- The iceberg raked the hull of the ship for 100 m, destroying the integrity of the six forward watertight compartments.
- Within 2 h 40 min the RMS Titanic sank with the loss of more than 1,500 lives.

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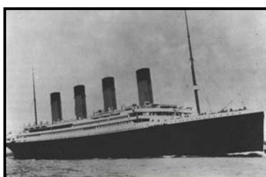
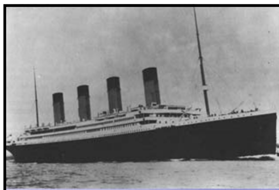
The Titanic

- Survivors disagreed about whether the *Titanic* broke into two parts as it sank or whether it sank intact
- On September 1, 1985, Robert Ballard found the *Titanic* in 3,700 m of water on the ocean floor
- The ship had broken into two major sections, which are about 600 m apart
- Between these two sections is a debris field containing broken pieces of steel hull and bulkhead plates, rivets that had been pulled out, dining room cutlery and chinaware, cabin and deck furniture, and other debris.



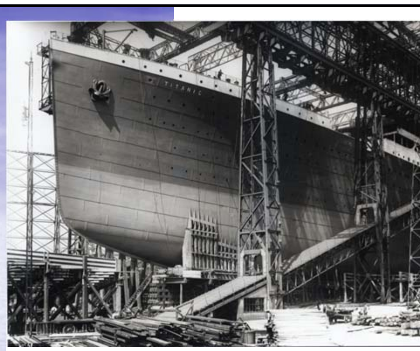
The Titanic

- Metallurgical examination and chemical analysis of the steel taken from the Titanic – provide clues to understand the hull damage
- The hull steel was as good as was available at the time the ship was constructed
  - BUT it was would not be acceptable for modern ship construction – brittle at low temperatures
  - The notch toughness showed a very low value (4 joules) for the steel at the water temperature (−2 °C) in the North Atlantic at the time of the accident
- The rivets were not up to the standards of the period



The Titanic

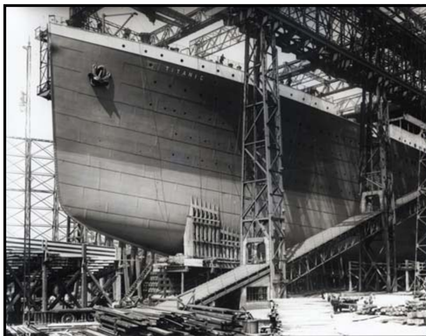
- Until recently - most assumed the iceberg had torn a huge gash in the starboard hull.
- 1985 – discovery of the Titanic wreck began new inquiries
- 1996 - an expedition found, under mud, not a large gash, but six narrow slits where bow plates appeared to have parted
- Naval experts suspected that **rivets had popped along the seams**, letting seawater rush in under high pressure.



The Titanic

Bow of the Titanic under construction – from a private collection of photos by one of the shipyard workers – the riveted plates show clearly.

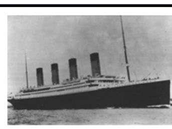
- 1997 - Dr. Tim Foecke analyzed the metallurgy of salvaged rivets
  - He found about three times more slag than in modern wrought iron
    - Slag is a glassy residue of smelting
    - Can make rivets brittle and prone to fracture
- Many of the rivets recovered from the Titanic contained high concentrations of slag.



The Titanic

Worse:

- In buying iron for the Titanic's rivets, the company ordered No. 3 bar, known as "best" — not No. 4, known as "best-best"
  - Shipbuilders of the day typically used No. 4 iron for anchors, chains and rivets
  - No 3 was cheaper and more available and the company purchased it for iron rivets used in part of the hull



The Titanic

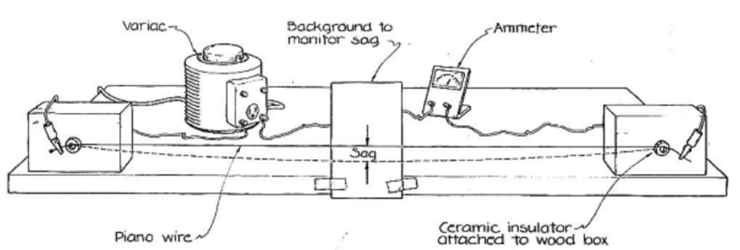
- The best rivets of the day were steel, not iron
  - Stronger
  - Workmanship better - machines could install them
- The rival Cunard line switched to steel rivets and used them throughout the Lusitania
- Harland and Wolff also used steel rivets
  - But - only on the Titanic's central hull, where stresses were expected to be greatest
  - Iron rivets were chosen for the stern and bow
- The bow is where the iceberg struck!
  - Studies of the wreck show that six seams opened up in the ship's bow plates
  - The damage "ends close to where the rivets transition from iron to steel"
- Better rivets might have kept the Titanic afloat long enough for rescuers to arrive before sinking - saving hundreds of lives

The Maine Maritime Steel Phase Apparatus

Very useful for demo of heat treatment effects on steel

The Maine Maritime Steel Phase Apparatus History

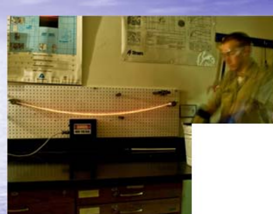
- May 1984, Scientific American article by Jearl Walker
- Apparatus by Charles Walton
- 2006 West Point apparatus brought to MMA
- MMA Apparatus designed for improvements in safety and in utility



Charles F. Walton's arrangement for heating piano wire

The Maine Maritime Steel Phase Apparatus Design and Construction

The Maine Maritime Steel Phase Apparatus – Design Materials to buy – Alligatorboard



- Alligatorboard is metal pegboard
- Easy to mount lab demos
- Wires are behind the board
- Mounted on threaded shafts with wing nuts – easy to remove for repairs
- Buy two sheets of white Alligator board, with turned edges 16” x 32” ($40)
- www.alligatorboard.com

The Maine Maritime Steel Phase Apparatus – Design
Materials to buy – steel wire

- From McMaster Carr
- 1080 Steel Music Wire, $4 for ¼ pound coil, approx. 100 feet
- Diameter is 0.029”
- http://www.mcmaster.com/

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25

The Maine Maritime Steel Phase Apparatus – Design
Materials to buy – ceramic standoffs

- Ceramic standoffs – purchased as navy surplus for $9 each – need to be sturdy and to provide screws for electrical connections to wire – I bought three to have a spare
- Hanging in background is a magnet with a 2’ insulated handle – made in lab – also a homemade plastic grabber with sponges fitted to it for safe quenching

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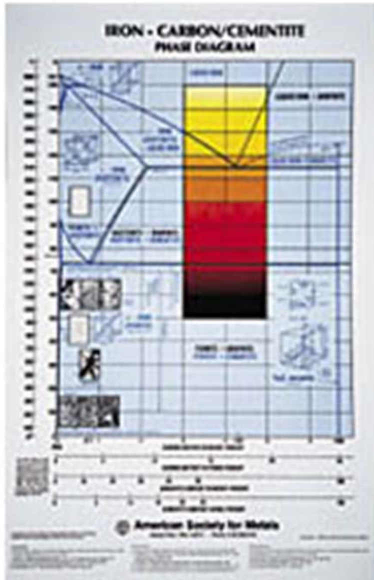
The Maine Maritime Steel Phase Apparatus – Design
Materials to buy – Lexan panels and mounts

- Lexan panels purchased from McMaster and cut in shop – cover entire length of wire with access door at right end
- Hinges from hardware store
- Supports are dowels cut in shop and fitted with wingnuts and threaded shafts both ends – stained black

Materials to buy:
Autotransformer (Variac)

- Need 15A model
- Staco Model #3PN1510B
- Approx. $750

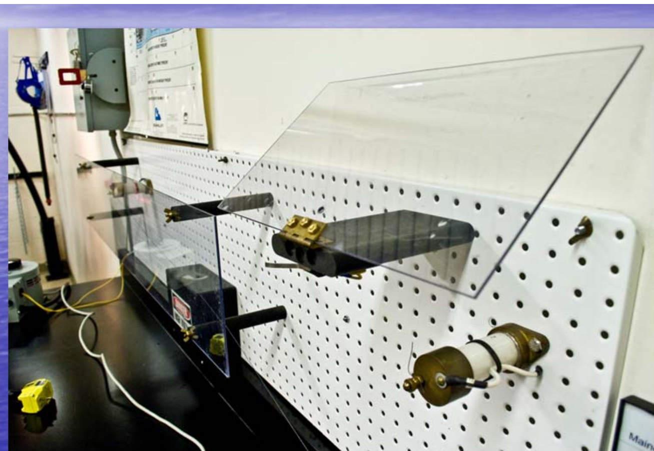


Materials to buy: Steel Phase Chart

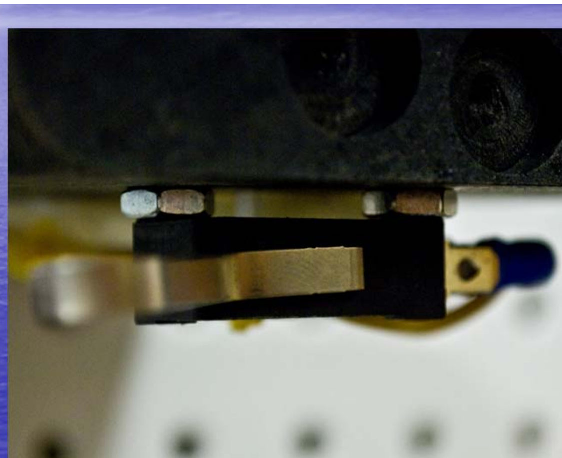
http://www2.asminternational.org/portal/site/edfas/AsmStore/ProductDetails/?vgnextoid=ac7b10a74e0f8110VgnVCM100000701e010aRCRD

- ASM Store #06423G
- $39
- Note colors, photos and crystal diagrams

Safety features
Lexan panels over the wire



Safety features
interlock switch on lexan door



Safety – removable power plug
stored when apparatus is not in use

Electrical connections box
Contains terminal block for AC and relay for interlock

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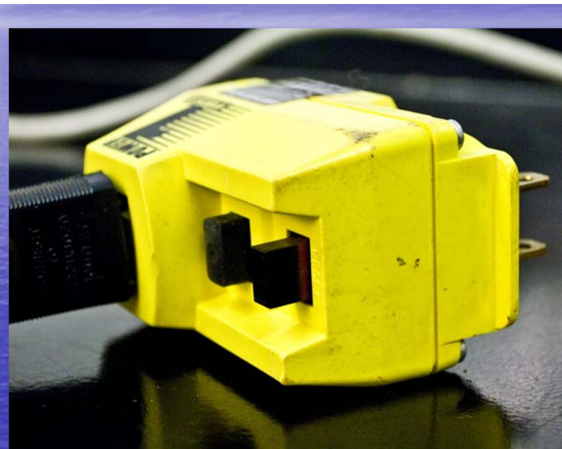
33

Safety features
- GFCI on power to unit



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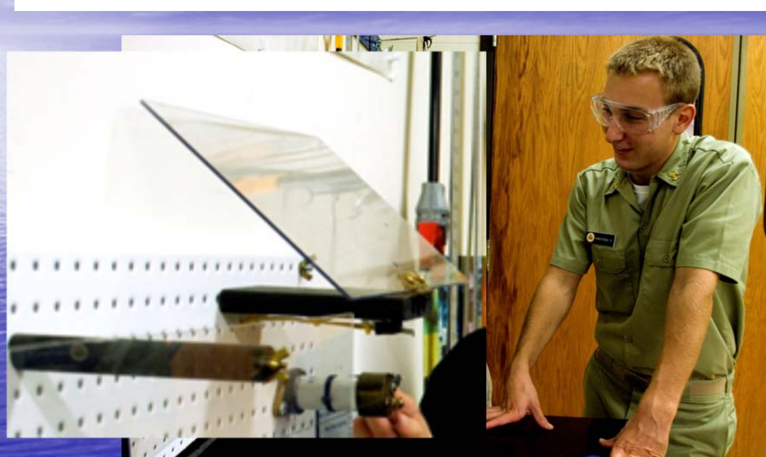
Safety features
Silicon electrical safety gloves
Power is off

Replacing the wire
You will need very good cutters – length is 5 feet



Installing the wire

Preparing to quench
– you will need a bucket and sponges

Wire under power
Notice the sag as steel becomes ductile

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39

Quenching the wire
(Power is off)

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40

Quenching the wire
Speed counts

Lab Demonstration
Heat Treated Steel

LAB OVERVIEW

- We often tensile test a steel sample first to see how much force it takes for the steel to break at room temperature
- We then heat treat a 1080 steel using the MMA Steel Phase Apparatus and look at the effect of the crystal structure changes
  - It becomes ductile when heated – sags several degrees
  - Carbon is diffused from the wire as it heats
  - If quenched when still above 740C it will change from a strong, ductile steel to a very brittle steel
  - Magnetism is interesting to observe as the steel is heated

LAB OVERVIEW

We ask the students to think about:

- Remember that a steel that is “too strong" will fail prematurely in a brittle fashion.
- Think about what can happen to the hull steel if there is an engine room fire
- Think about the possibility of a crack traveling if a hatch is cut with square corners (stress concentrators)
- Think about the effect of overloading the hull on design stress levels

The Maine Maritime Steel Phase Apparatus – a very useful demo tool

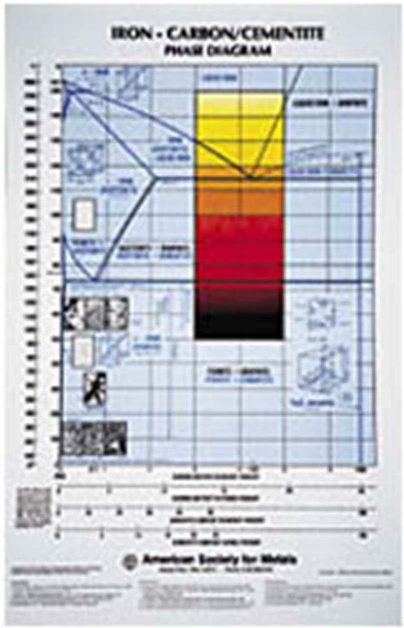
- Heat treat – how steel changes when heated and quenched
- Phase diagram for steel
- Crystal structure changes and their characteristics – hands-on look
- Lab demo

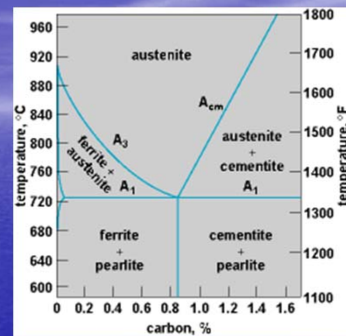
PHASES OF STEEL

The Steel Phase Apparatus has proven to be a very effective hand-on tool for relating theory of steel phases to practice – for engineers, for deck students, for STEM classes

- We review the three unique thermodynamically stable phases of iron and carbon atoms in carbon steels
- Ferrite (α) is the phase with a body-centered cubic unit cell,
  - Austenite (γ) is the phase with a *face-centered cubic unit* cell,
  - Cementite (Fe_3C, also known as iron carbide,) is the phase with an orthorhombic unit cell.
- The phase or combination of phases that actually exists in a given steel depends on temperature and composition - in this experiment we look mostly at temperature effects on strength, brittleness, carbon content, and magnetism

PHASE DIAGRAM FOR STEEL

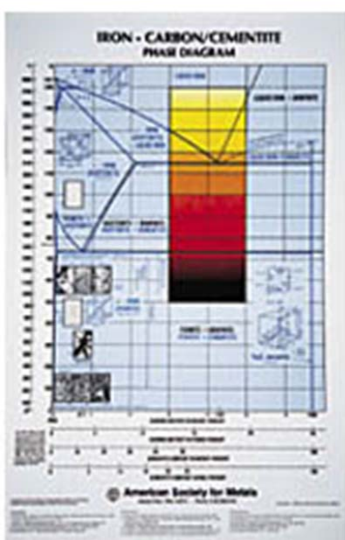




Phase diagram –
Critical temperatures in carbon steels and constituents which are present in iron-carbon alloys upon slow cooling.

47

PHASE DIAGRAM FOR STEEL



This particular chart is useful as it includes

- Critical temperatures for carbon compositions
- Microphotographs
- Crystal structures
- Colors
- Degrees C and dig F

- Very useful for students to relate theory to practice

- A copy is on the wall over the apparatus and is very useful

48

DISCUSSION QUESTIONS:

- 1. Discuss what is happening microstructurally as the steel strips are heated to "orange-red" and if allowed to cool SLOWLY. Include phases and crystal structures.
- 2. Describe what happens when steel with sufficient carbon is quenched rapidly. What new phase is created? How does the strength, ductility, and hardness compare to the original, unquenched steel?
- 3. Why is the formation of austenite important in the processing of steel?
- 4. Briefly sketch and label the various microstructures of the following equilibrium and non-equilibrium cooled 1080 steels (include important microstructure and a few words on property considerations):
  - Coarse pearlite (FP)
  - Fine pearlite (CP)
  - Bainite (B)
  - Untempered Martensite (M)
  - Tempered Martensite (TM)
  - Spheriodite (S)

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Any questions?