Impact Testing

History

In the tensile testing experiment, we pulled metal samples and watched them stretch until they broke in a ductile manner. If we had tested brittle materials, they would not have stretched; instead, they would have snapped suddenly. Some materials are ductile at room temperatures, while others are brittle at room temperature.

If we change the temperature, we can change the failure mode. Some materials that are ductile at room temperature can become brittle at low temperature (like bubble gum); other materials that are brittle at room temperature can become ductile at high temperature (like glass). We can measure this change in properties with impact testing.

Let's look at the history of impact testing:

- **1824** Publication of the first scientific paper to propose theories of impact resistance. The authors were interested in cast iron, which was widely used for structural components of machines, bridges, and buildings.

- **1849** Cast iron bridges in Great Britain were cracking due to the impact loading from trains. Before the railroads, heavy goods moved by canal boat. Some canals were elevated across valleys with bridges, but the load applied to the supports did not change as a canal boat traversed the bridge, because the weight of each boat displaced an equal weight of water. Trains are different: as a heavy locomotive traverses a bridge, the supports see a greater load. The train is moving fast, so the support structure sees a sudden change in load...an impact load.

- **1857** The first impact testing machine was developed to test actual finished parts.

- **1898** Founding of ASTM, the American Society for Testing and Materials,\(^1\) to address railroad rail failures. ASTM is a voluntary standards organization which writes standards for materials and test procedures.

- **1898** S.B. Russell publishes a scientific paper on pendulum impact testers, in which a heavy weight at the end of an arm smashes into a test specimen. At this time, there were two other types of tester in common use: [1] drop weight, in which a heavy weight is dropped on the test specimen, and [2] flywheel, in which the momentum of a rotating wheel is used to smash a test specimen.

- **1901–05** G. Charpy modified Russell’s pendulum tester to accept a standardized test specimen. Prior to Charpy, impact testing was done on finished parts, such as pipes, gun barrels, railroad rails, etc. Charpy thought it made more sense to test materials than components. Once you test a particular material, you can apply the results to all the different finished products that use the material.

- **1933** ASTM adopted the two major pendulum test methods.

- **1940** The U.S. Navy became interested in impact testing. Here's why:

  This graph shows the gross tonnage of Allied shipping that was built (blue) and sunk (red).\(^2\) In the earlier part of the graph, the Axis powers were sinking ships faster than the Allies could build new ones. The Allies were taking a pounding from enemy planes, ships, and submarines, so there was a big effort to build as many ships as possible in a short timespan. The U.S. Navy organized shipyards on both coasts to build a standardized ship. Everyone used the same plans, so there were economies of scale and economies of time. Instead of taking years to build, these ships eventually were completed in weeks.

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1. Since 2001, known as “ASTM International”.
The *Liberty ships* were assembled in a new way. Previously, steel ships were assembled by riveting steel plates together, but the Liberty ship design called for welded plates. The reason the Navy got interested in impact testing is they had a problem with fracture. Liberty ships were failing at a rate of 30%. The S.S. Schenectady cracked in two the day after it was launched.\(^3\) It didn’t sink...you can see daylight under the hull, where it broke in two. The bow and the stern were heavier than the mid-ships. Many of the ships cracked in the open ocean, and returned to port missing the bow. There were really three problems with the ships:

1. The hatchways were square, to make manufacturing easier. Unfortunately, these square internal corners acted as stress concentration sites...as sources of cracks.

2. The steel used in the hull contained excess sulfur and became brittle when exposed to the temperature of seawater.

3. The welds were somewhat brittle, so once a crack developed, it ran easily along the welds.

### Ductile to Brittle Transition

Here’s a graph that shows the transition from ductile to brittle behavior in a low-carbon steel.\(^4\) At higher temperatures, the steel can absorb a lot of impact energy before failure. At lower temperatures, the steel absorbs a small amount of impact energy before it fractures, so we say it’s brittle.

The temperature range where we go from ductile to brittle behavior is the *ductile-to-brittle transformation temperature*. Plain carbon steels are susceptible to this phenomenon. Higher carbon steels are not as resistant to impact...they’re more brittle to begin with, so the effect is real but much smaller.

Stainless steels with an FCC crystal structure do not suffer from ductile-to-brittle transformation, so they can be used more reliably at high and low temperatures. This is the reason stainless steel tubing is used for liquid nitrogen.

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\(^3\) The ship fractured at the dock in Portland, OR, sitting in 40°F water. File TankerSchenectady.jpg, from Wikimedia commons, is in the public domain in the U.S. because the photograph was taken by a U.S. government employee as part of the photographer's official duties.

The hand-tool industry is interested in the brittleness of steels. Think about a carpenter’s hammer. We want the hammer head to retain its shape after many uses, so it’s got to resist deformation. At the same time, we never want the hammer head to chip, which is how it would fail in a brittle mode.

Here’s another graph\(^5\) that shows carbon steels with a range of carbon content. We can learn several things from the graph:

- Low-carbon steels have higher impact resistance than high-carbon steels.
- Low-carbon steels have lower ductile-to-brittle transition temperature ranges than high-carbon steels, and the ranges are narrower.
- There’s a huge difference between 0.1\% and 0.2\% carbon...the impact energy at high temperatures \textit{doubles}.

One popular explanation for the sinking of the Titanic is that the hull became brittle in the cold North Atlantic.

A researcher at the National Institute for Standards and Testing conducted tests on samples from the Titanic, along with modern shipbuilding steel.\(^6\) He prepared specimens so they would break along the grain of the hull plates (longitudinal) and across the grain (transverse). The 20 ft.lb. line marks a common definition of ductile-to-brittle behavior for low-carbon steels.

- The Titanic’s hull would have been brittle in tropical oceans too.
- Modern steel is better…it has a lower ductile-to-brittle transition temperature, and it has better room-temperature impact resistance.

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\(^6\) Data from Tim Foecke, \textit{Metallurgy of the RMS Titanic}, NIST internal report NIST-IR 6118.
This impact energy graph tells us 2 things:

We can use heat treatment and alloying to get better impact resistance at low temperatures.

There’s a large range of data points within any one category of material. Look at mild steel at room temperature…the impact resistance ranges from 20 to 100 ft.lb…a factor of 5 difference!

The data you take in the lab experiment will include a lot of scatter. This graph shows the range of data that can occur within the same kind of material. Sources of variation include specimen preparation technique, orientation with respect to rolling direction, heat treatment, composition, and the actual radius of the base of the V-shaped groove.

Here’s an unusual impact graph, for pure tin. It starts with a standard S-shaped curve, then it drops back to zero as the temperature gets higher. As we get closer to the melting point of the metal, it gets weaker and softer…so it can’t take as much impact.

The same is true for steel, but we don’t normally measure the impact resistance of steel at 1400°F.

The nuclear power industry is interested in impact testing because exposure to temperature and radiation causes structural members in nuclear power plants to become brittle. Therefore, specimens are cut from structural components for impact testing. If the material has become brittle, then the industry uses induction heating to anneal the metal in-place, so it’s not as brittle.

We haven’t built a new nuclear plant in the US since the 1970s, so all the plants running now are getting old. The construction bonds have been paid off…they’re essentially cash cows to the utilities that run them. Decommissioning will be really expensive, so every extra year of life is gravy for the utilities, saves construction costs for a new plant, and keeps us from being dependent on foreign oil.

Another reason for doing impact testing is to measure notch sensitivity. Any deep scratch in a machined surface can act as a stress concentrator. Some materials are more sensitive to this effect than others. We can test specimens with different size scratches to determine how sensitive a material might be.

If we want to test notch sensitivity, then we need specimens with and without notches. The slide from class shows some typical specimen geometries. In the lab, we will use specimens with a V-notch, like the one in the center.

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We’ll place the specimen in the holder at the bottom, lift the pendulum up, then let it swing and break the specimen. The height that the pendulum swings to will indicate how much energy is absorbed. The higher it swings, the less energy is absorbed by the specimen.

We’ve already said that some materials are more notch-sensitive than others. Here’s some data for ductile cast iron and gray cast iron. Ductile cast iron is highly sensitive to notches, while gray cast iron is not. Think about the microstructure: ductile cast iron has round, spherical graphite particles. One deep scratch on the surface creates a stress concentration, weakening the material. Gray cast iron has graphite flakes, so it’s filled with trillions of tiny notches already. Any additional scratches on the surface will make no difference.

In the lab, we’re going to break multiple samples at multiple temperatures, using liquid nitrogen, dry ice, ice water, room temperature, and two hotplates. You will plot the impact energy vs. temperature, and figure out what the ductile-to-brittle transition temperature is. Next, you’ll create an S-shaped curve to fit the data.

The series of graphs at the right show the Titanic data (longitudinal sample), with four different curves.

A straight line does not fit the data at all.

An exponential curve fits the dataset at low temperatures only.

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A logarithmic curve fits the dataset at high temperatures only.

MS Excel does not include regression software for creating S-shaped curves, so you will need to draw a freehand curve using the software. Unfortunately, the method for creating this curve changes with each new iteration of Excel (and it’s different between Windows and Mac operating systems), so you will have to find it on your own.

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