UOWD
Autumn 2023
ENGG103-Materials in Design Laboratory

EXPERIMENT 2 –IMPACT STRENGTH OF MATERIALS

1. Objectives
The objectives of this experiment are to consider the different ways in which materials fail, to investigate the effects of strain rate and temperature on the "strength" of a material, and to compare brittle and ductile failures in metals.

2. Background
The "strength" of a material is a fundamental mechanical property used by engineers when designing structures (or components/devices etc.) to ensure that mechanical failure is avoided. Callister [1] defines tensile strength as, *"the maximum engineering stress, in tension, that may be sustained without fracture."* In this experiment, the effect of the testing environment on the failure strength will be examined.

Ductile or Brittle Fracture?
For fracture of any material to occur there must be cracks within the sample and one (or more) of the cracks must propagate until failure. Ductile fracture occurs when there is substantial plastic deformation around the crack tip during crack propagation. Plastic deformation occurs when atomic bonds within a material are severed and reformed. Because of this mechanism, plastic deformation (unlike elastic deformation) is permanent once a sample is unloaded.

Brittle fracture occurs when there is very little or no plastic deformation around an advancing crack tip. Brittle materials absorb little energy during the fracture process and can often fail catastrophically and suddenly.

Ductile to Brittle Transition Temperature (DBTT)
It is possible for some metals Body Centred Cubic, (BCC) and Hexagonal Close Packed, (HCP) to behave in a ductile manner at higher temperatures and in a brittle manner at lower temperatures. The change in behaviour can be quite dramatic over a small temperature range. This is known as the Ductile to Brittle Transition temperature (DBTT). FCC (Face Centred Cubic) metals do not have such a strong transition; this is because of the large number of the slip systems in metals with a FCC structure compared to BCC or HCP structures. See Figure 1.

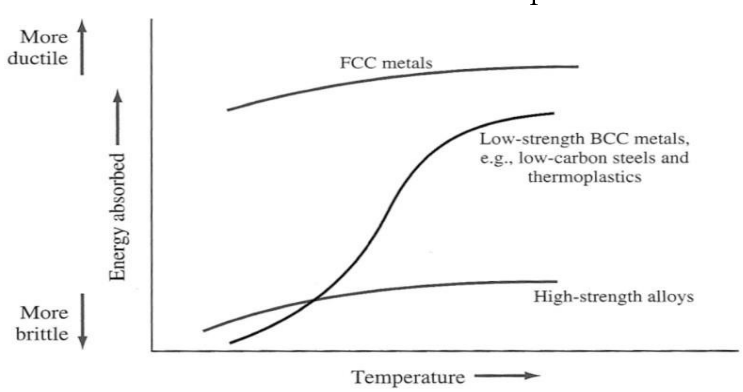

Figure 1 – Ductile to Brittle Transition Behaviour with Temperature for different types of metals [2] p 287.

Ignorance of the DBTT in the early 20th century lead to catastrophic failures, such as the Titanic in 1912 and brittle fracture of the Liberty ships in World War II. These structures were constructed from steel, a BCC metal which is particularly prone to brittle failure at temperatures close to 0°C. To complicate matters further the DBTT temperature in steel is dependent upon the sulphur content. The steel the Titanic was made of contained 0.06% sulphur and metallographic examination of specimens that were retrieved from the ship's hull revealed that it contained 25 mm long, elongated MnS stringers that essentially acted as cracks and caused the brittleness. Quality steels today contain perhaps 20 parts per million sulphur and do not contain MnS stringers. Hence their DBBT is significantly lower and they can easily be used at temperatures far below the freezing point of water.

The Titanic began its maiden voyage to New York just before noon on April 10, 1912, from Southampton, England. Two days later she struck an ice berg, damaging the hull so that the six forward compartments were ruptured. The flooding of these compartments was sufficient to cause the ship to sink within two hours and 40 minutes, with a loss of more than 1,500 lives. *A metallurgical analysis of steel taken from the hull of the Titanic's wreckage reveals that it had a high ductile-brittle transition temperature, making it unsuitable for service at low temperatures; at the time of the collision, the temperature of the sea water was -2°C. The analysis also shows, however, that the steel used was probably the best plain carbon ship plate available at the time of the ship's construction.* [3].

Figure 2 – the Sinking Titanic – image source http://interesting-facts.org/page/2

Liberty ships were cargo ships built in the United States during World War II. There were nearly 1,500 instances of significant brittle fractures, a small number of which completely broke in half. "For example, on 24 Nov 1943, SS John P. Gaines broke in half and sank, taking 10 men with her. The blame originally was on the new welding method and the careless haste to build large quantities of ships, *but Constance Tipper of Cambridge University in England, Britain found out that it was actually the cold temperatures of the North Atlantic that made the steel brittle, leading to cracking in some instances. Welding still had a role in it, however, as welding allowed small cracks to grow longer over time (something riveting would prevent)*". Quote from reference [4]

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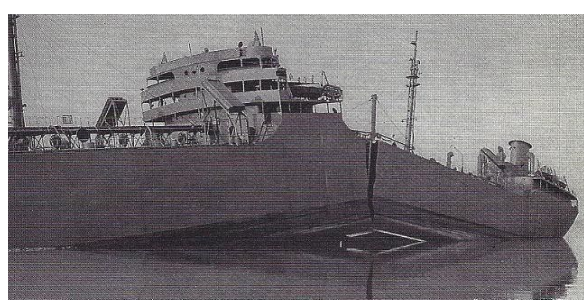


Figure 3 – Liberty Ships catastrophic failure by fracture http://www.understandingphysics.org/chapters/04/4-1.php

How Do We Measure DBTT

To measure the DBTT we need to assess the energy absorbed during fracture. Commonly this is achieved using the Charpy impact test shown in Figure 4. A standard sample is made with a small notch machined into one side. The notch acts as a stress concentrating site enabling fracture to occur in a controlled manner in the vicinity of the notch.

The notched sample is loaded into the impact tester in such a manner that a hammer on the end of a pendulum strikes the sample from behind, on the opposite face to the notch. If the sample is ductile then much of the kinetic energy from the force of the hammer is absorbed into the microstructure around the notch before fracture. Once the sample fractures the hammer will continue its trajectory with a speed directly related to the amount of energy it retained after impact. When a very brittle sample is tested the hammer will not impart a large amount of kinetic energy to the sample to facilitate fracture, and its swing after impact will still be energetic. The energy of the swing can be measured by the scale on the Charpy impact test machine. These numbers can be converted directly into fracture energy G_c.

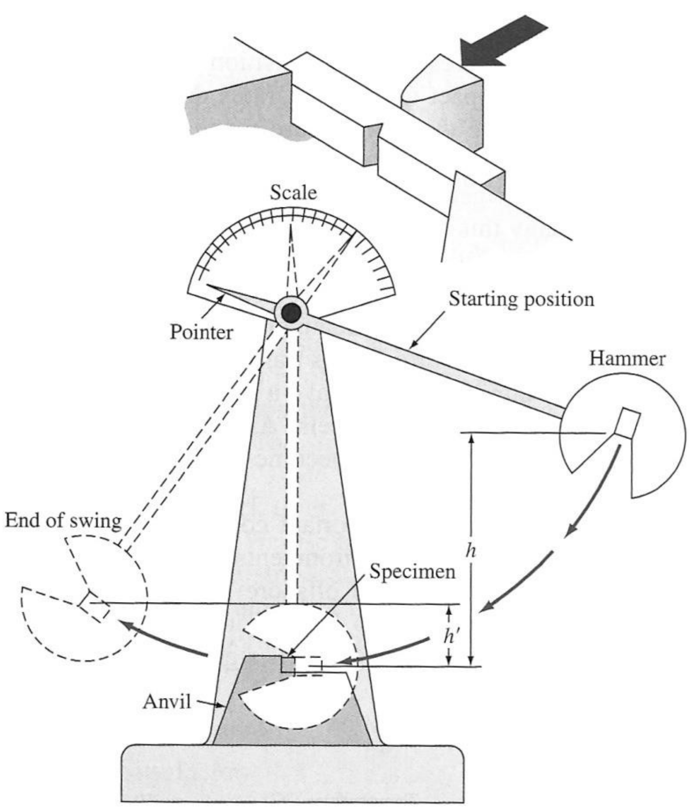


Figure 4 - Schematic of Charpy Test from W.F. Smith and J. Hashemi, [2] p287.

Impact Energy and Fracture Mechanics

Impact tests were developed because it was practical to ascertain the fracture behavior of materials under the most severe conditions, such as low temperature, high strain rate (or impact) and in a triaxial stress state (such as that surrounding a notch). The impact or fracture energy G_c is the amount of energy required to fracture the material and can be estimated from the change in kinetic energy of the striking object that causes the material to fail. In the simplest case, the fracture energy G_c of a material can be calculated from.

$$\sigma_c = \left(\frac{G_c E}{\pi a} \right)^{1/2} \quad \text{.........................} \quad (1)$$

Where G_c = fracture energy (J/m^2)
E = elastic modulus (N/m^2 or Pa)
a = ½ length of size of largest crack (m)
σ_c = Critical stress required to cause crack propagation(strength)

Equation (1) shows that the strength is higher when more energy is needed to cause fracture (i.e. G_c is bigger). Notice that the units of G_c are Joules per cross-sectional area (J/m^2), indicating that this is a measurement of the energy absorbed by creating the new surface area of the crack.

An impact test will give us a value of impact strength but the results remain qualitative and greatly dependent upon test conditions. Therefore, the impact strength determined by impact tests is rarely used for design purposes. Because of these problems, it is more common to refer to an impact or fracture <u>energy</u> rather than impact <u>strength</u> (stress).

Fracture mechanics provides a more quantitative approach such that the fracture properties of different materials can be compared by measuring the critical plane strain fracture toughness K_{IC}. K_{IC} is measured by loading a material with known crack length under plane strain* to a critical tensile stress (σ_c) required for crack propagation,

$$K_{IC} = f\,\sigma_c \sqrt{\pi a} \text{...} (2)$$

Where f = a geometrical constant
a = ½ length of largest internal crack (m)
σ_c = Critical stress required to cause crack propagation

Values of K_{IC} can be used to evaluate and compare different materials for design purposes. Whereas G_c is more of a quality control measurement or an in-house laboratory test to compare the fracture behavior of materials under specific conditions. It has particular application in determining the DBTT of metallic materials.

In this laboratory experiment, you will investigate how the test temperature affects the fracture energy G_c of different materials (details of which are provided in Table 1) under impact conditions and construct a DBTT curve.

3. Experimental Procedure

The equipment we use will be a specially built "mini-Charpy impact Tester with 25 Nm capacity as shown in Figure 5.

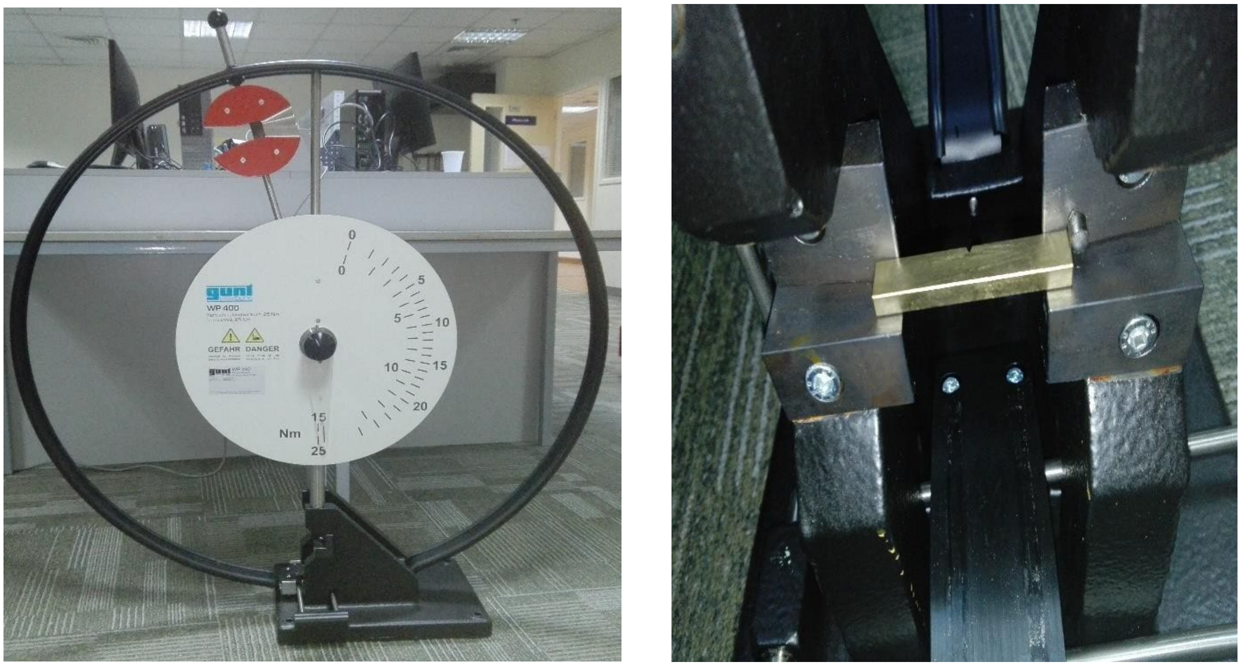


Figure 5 – Mini Charpy Impact Tester and Notched sample positioned in front of the hammer.

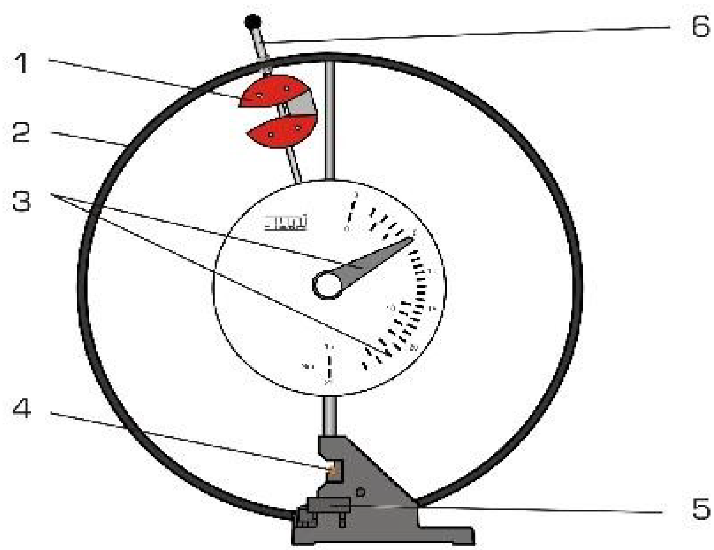


Figure 6 – Mini Charpy Impact Tester Schematic. 1. hammer with removable additional weights, 2. protective ring, 3. scale with drag pointer, 4. notched bar impact specimen, 5. two-hand trigger and brake, 6. hammer fixing

Samples of different materials will be tested on the Mini Charpy Tester after they have been equilibrated at different temperatures. The samples will be tested at room temperature. This means that specimens will either heat up or cool down when taken from their equilibration chamber. The specimen temperature will be estimated at the time of testing using a thermocouple probe.

Mini Charpy Test Procedure:

1. Press the two-hand trigger and brake with your foot.
2. Lift the hammer to the position as shown in figure 6 until its locked in by hammer fixing.
3. Reset the drag pointer to 25 Nm position.
4. Take the notched sample of your chosen material and measure the thickness, measure the required dimension at r.t.p using a Vernier caliper.
5. Take one sample and place it in the heater to elevate the temperature above room temperature and take another sample and place it in the freezer to cool it below room temperature
6. Monitor the sample temperature using the thermocouple probe until it reaches the desired test temperature.
7. Place the sample at the r.t.p in the Charpy Impact Tester.
8. Move away from the tester and ensure the test area is clear.
9. Release the hammer by lifting the hammer fixing while pressing the two-hand trigger/brake with your foot.
10. Record the final position of the pointer after impact in Table 2 (also record the test temperature).
11. Repeat step 1-10 for samples above room temperature and below room temperature.
12. Observe the fracture surfaces of samples tested at room temperature, below room temperature and make sketches in the space given in Section 5.

Each sub-group should do 3 tests and your group should cover the temperature range (+2^{o}C to +100^{o}C) by carefully monitoring the sample temperature.

4. Data Analysis

Convert the pointer positions to fracture energy (W in J/mm^2) using the equation below.

$$W = E_{abs} / [(t-d) \times w] \quad (3)$$

where E_{abs} is the energy absorbed (J)

t is the sample thickness

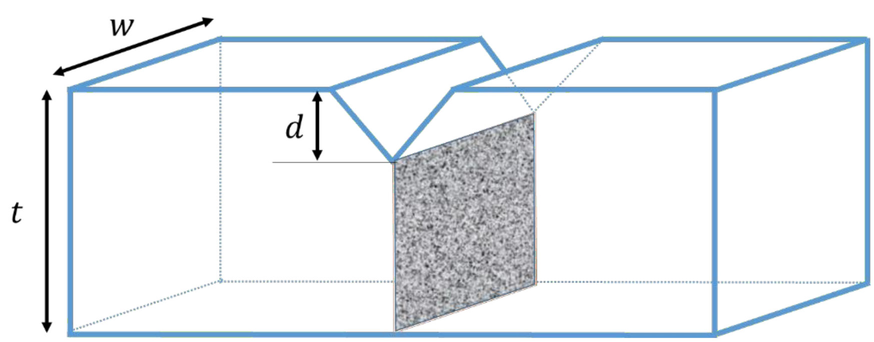
d is the notch depth

w is the sample width

5. Results

Table 1: Results from Mini-Charpy Impact Testing of V-notched samples.

Material	Sample Temperature	Width w	Thickness t	Depth d	Absorbed Energy E	Fracture Energy W
	(°C)	(mm)	(mm)	(mm)	(J)	(J/mm^2)
Brass	0					
	21					
	100					
Aluminum	0					
	21					
	100					
Steel 15 HRC	0					
	21					
	100					
Steel 25 HRC	0					
	21					
	100					



$$W = \frac{E_{abs}}{w(t-d)}$$

Report requirements

1- **Cover page**
-Includes your name, ID, course title and code, name of teachers, etc.

2- **Results** **<u>(5 marks)</u>**

- Complete the results table in the results section by calculating the Fracture toughness of the tested materials.
- Plot the Fracture energy (J/mm^2) vs Temperature (°C) for all materials on the same graph.

3- **Discussion** **<u>(5 marks)</u>**

- Write a comprehensive discussion, stating the scope of the experiment, the results, and how your results relate to the theory.
- Compare the materials.
- Explain the possible sources of errors.
- Explain the method used to obtain values more than 25 Nm, despite the capacity of the machine being 25 Nm.
  Hint: if a sample does not break, this means it has absorbed 25 Nm of energy with that hit.

References:

[1] W.D. Callister Jr., Materials Science and Engineering: An Introduction, 4th ed., John Wiley and Sons, 1997
[2] W.F. Smith and J. Hashemi, Foundations of Materials Science and Engineering, 5th Edition, McGraw-Hill, 2010
[3] World War II Database, Liberty-class Merchant Vessel http://ww2db.com/ship_spec.php?ship_id=391
[4] K. Felkins, H.P. Leighly, Jr., and A. Jankovic, JOM, 50 (1) (1998), pp 12-18

[5] Gunt Hamburg (2017), WP 400 Impact test, 25Nm [Online] available at: http://www.gunt.de/en/products/engineering-mechanics-and-engineering-design/testing-of-materials/impact-bending-test/impact-test-25nm/020.40000/wp400/glct-1:pa-148:ca-35:pr-1621 [Accessed 19 October 2017]

[6] Bestech (2017), Young's Modulus of some common material [Online] available at: http://www.bestech.com.au/wp-content/uploads/Modulus-of-Elasticity.pdf [Accessed 19 October 2017]