ME 3305 MATERIALS' SCIENCE

Lab: Charpy Impact Test

Objectives

This lab component will familiarize the students with the procedure for determining "toughness" using Charpy impact test. Students will learn:

1. How to measure the impact resistance of metallic materials using Charpy impact test;
2. Effect of temperature on the material impact toughness;
3. Effect of composition (carbon content) on the impact toughness.

Background

Fracture Toughness

Fracture toughness is an important material property to consider when designing load-bearing structures because catastrophic failures (fracture, rupture, etc.) should always be avoided. Fracture toughness is generally defined as the amount of energy absorbed when *fracturing* a material. Although toughness is related to the area under the curve of load versus elongation for a tensile test, separating the energy due to elastic deformation from that due to plastic deformation is difficult.

Various tests have been developed to measure fracture toughness, many of which rely on dedicated testing configuration, sample preparation, and numerical calculation. When such tests are not available or too expensive/time consuming to conduct, impact tests such as Charpy (simple-beam) test or Izod (cantilever-beam) test can be utilized. The Charpy and Izod impact tests are currently widely used as an economical quality control method and to evaluate the relative toughness of materials. See the ASTM E23_Standard Test Methods for Notched Bar Impact Testing of Metallic Materials.

Charpy Impact Test

A Charpy impact testing machine is basically composed of a swinging pendulum (or a hammer) and an anvil. A bar sample with a V-notch is placed on the anvil. The initial position of the hammer has a relative height of h_1 (with respect to the sample). It can be seen that the potential energy of the hammer before release is equal mgh_1. After release, the potential energy decreases and the kinetic energy increases until just before impact. At a point of impact the amount of energy necessary to fracture the sample is dissipated. As the hammer continues its swing the remaining kinetic energy is again converted to potential energy, the process being completed when the pendulum reaches its farthest excursion, where potential energy is mgh_2. The difference between two potential energies $mg(h_1 - h_2)$ is the energy absorbed by fracture – the Charpy impact energy.

On impact, the sample deforms elastically until yielding takes place (plastic deformation), and a plastic zone develops at the notch. As the test sample continues to be deformed by the impact, the plastic zone work hardens. This increases the stress and strain in the plastic zone until the sample fractures. The Charpy impact energy absorption (or loss) therefore includes the elastic strain energy (usually not a significant fraction), the plastic work done during yielding and the work done to create the fracture surface. *Therefore, impact energy loss is different than the fracture toughness defined in fracture mechanics*.

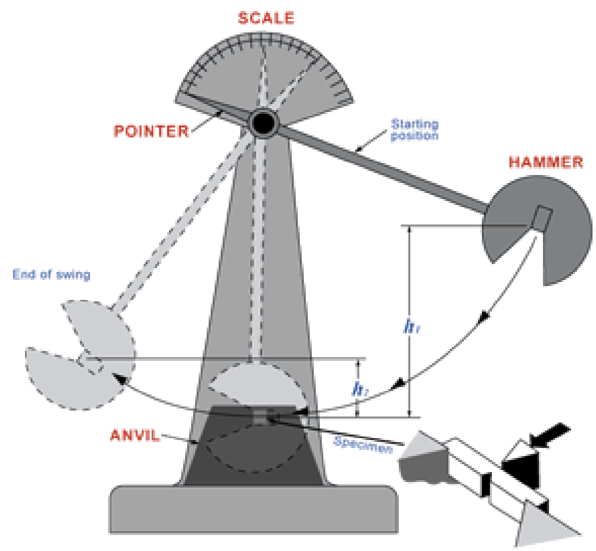
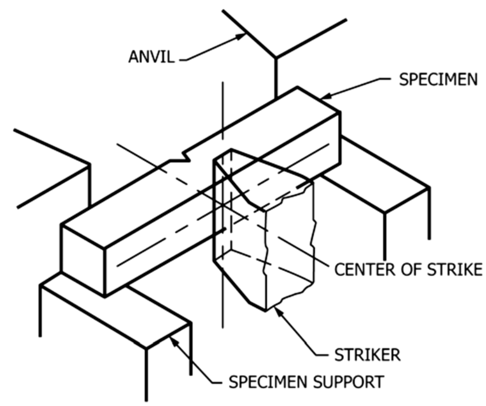


Figure 1. Schematic of Charpy impact test.



Factors Affecting the Impact Energy Loss

The impact energy loss is affected by a number of factors, such as:

- Materials properties including yield strength and ductility.
- Geometry of the notch.
- Temperature and Strain Rate.
- Fracture Mechanism.

Yield Strength and Ductility

Increasing the yield strength of a metal by processes such as cold work, precipitation strengthening and substitutional or interstitial solution strengthening generally decreases the ductility, which is the amount of plastic strain to failure.
Increasing the yield strength by these mechanisms therefore decreases the Charpy impact energy since less plastic work can be done before the strain in the plastic zone is sufficient to fracture the test sample. An increase in yield strength can also affect the absorption of impact energy by causing a change in the fracture mechanism.

Notches

The notch in the test sample has two effects and both can decrease the impact energy. First, the stress concentration at the notch causes yielding or plastic deformation to occur at the tip of the notch. A plastic hinge can develop at the notch, which reduces the total amount of plastic deformation in the test sample. This reduces the work done by plastic deformation before fracture. Secondly, the constraint of deformation at the notch increases the tensile stress in the plastic zone. The degree of constraint depends on the severity of the notch (depth and sharpness). The increased tensile stress encourages fracture and reduces the work done by plastic deformation before fracture occurs.
Some materials are more sensitive to notches than others and a standard notch tip radius and notch depth are therefore used to enable comparison between different materials. The Charpy impact test therefore indicates the notch sensitivity of a material.

Temperature and Strain Rate

Since the Charpy impact energy loss comprises mostly of the plastic work of yielding of the sample, it is affected by factors which change the yield behavior of the material, such as temperature and strain rate, through their effect on the behavior (motion) of the dislocations.
Increasing the yield strength by low temperatures or high strain rates decreases the ductility, and therefore decreases the Charpy energy loss. The yield strength of body centered cubic (bcc) metals is more sensitive to strain rate and temperature than that of face centered cubic (fcc) metals. The Charpy impact energy of bcc metals such as **ferritic** carbon steel therefore has a stronger dependence on strain rate and temperature than that of fcc metals such as aluminum, copper and **austenitic** stainless steel.

Figure 2. Body centered cubic (atomic packing factor, APF = 0.68) versus face centered cubic (APF = 0.74) structure

Fracture Mechanism

The Charpy energy loss is affected by changes in the fracture mechanism. Metals usually fracture by microvoid coalescence in which the plastic strain causes void nucleation around inclusions. They grow and link up until failure occurs. In bcc metals, failure can also occur by cleavage along the {001} crystal planes at a critical tensile stress. As the yield strength of the metal is increased, the tensile stress in the plastic zone can become sufficiently high for cleavage to occur. The fracture mechanism in a ferritic carbon steel therefore changes from microvoid coalescence to cleavage as the yield strength increases. This can be caused by an increase in strain rate or a decrease in temperature. The work of fracture of cleavage is much less than the work of fracture of microvoid coalescence since it involves much less plastic deformation. The change in fracture mechanism therefore causes a sharp **ductile to brittle transition** in the Charpy energy loss.

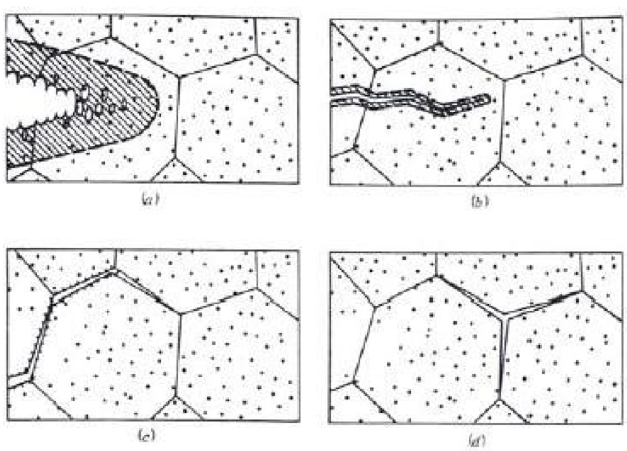


Illustration of four different fracture modes: (a) micro-void coalescence which is the ductile mode, and few brittle fracture modes such as (b) cleavage (trans granular), (c) low stress intensity intergranular, (d) high stress intensity intergranular [Metallurgical and Materials Transactions B v.3, 441–455(1972)]

The Ductile to Brittle Transition

As mentioned above, decreasing temperature can change the fracture mechanism and therefore lead to the ductile to brittle transition. The Charpy impact test can be used to determine this transition behavior of a metal. It is very important to realize that the ductile to brittle transition is defined in terms of the fracture energy: a brittle fracture results in a low energy fracture and a ductile fracture results in a high energy fracture. Some confusion often occurs because we can also use the terms brittle and ductile to describe fracture mechanisms. Microvoid coalescence is a ductile fracture mechanism and cleavage is a brittle fracture mechanism. However, it is possible for a low energy brittle fracture to occur by either ductile microvoid coalescence (e.g. cold worked brass) or brittle cleavage (e.g. ferritic steel at low temperature). You should always be aware of both the toughness and the fracture mechanism.

The ductile to brittle transition curve records the effect of temperature on the impact energy. The impact energy generally decreases with decreasing temperature. A sharp transition, where the energy changes by a large amount for a small temperature changes, can occur when there is a change in the fracture mechanism. If the material has a sharp ductile to brittle transition, then a **ductile to brittle transition temperature (DBTT)** can be defined below which the material has poor toughness. This can be used as a guideline for the minimum service temperature. It is less easy to do this in materials with a smooth transition from ductile to brittle behavior.

In addition to the impact energy there are two further features that can be measured and may be found as a requirement in some specifications. These are **percentage crystallinity** and **lateral expansion**. The appearance of a fracture surface gives information about the type of fracture that has occurred - a brittle fracture is bright and crystalline, a ductile fracture is dull and fibrous. **Percentage crystallinity** is therefore a measure of the amount of brittle fracture, determined by making a judgement of the amount of crystalline or brittle fracture on the surface of the broken specimen.

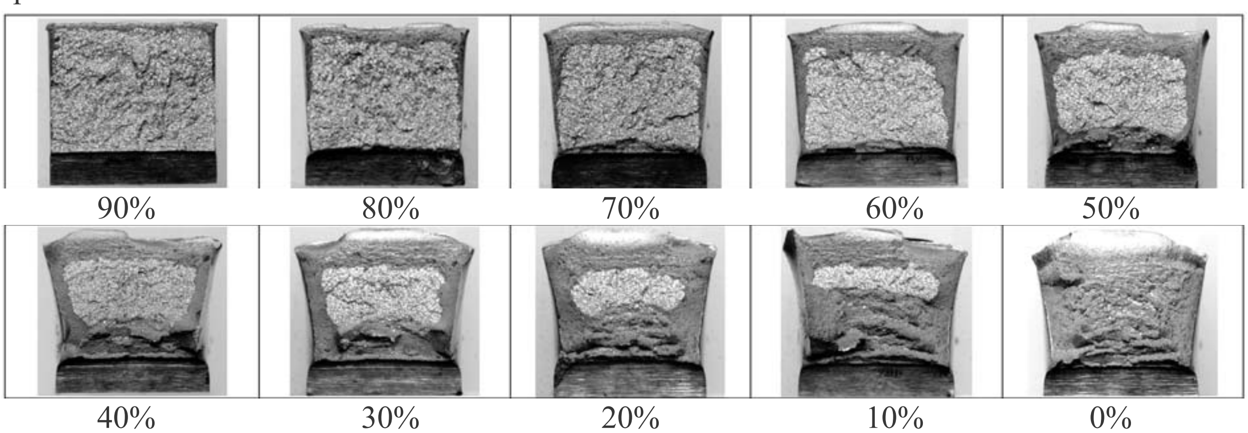


Figure 3. Percentage of crystallinity (brittle) fracture versus shear (ductile) fracture

Lateral expansion is a measure of the ductility of the specimen. When a ductile metal is broken the test piece deforms before breaking, a pair of 'ears' being squeezed out on the side of the compression face of the specimen, as illustrated on the right. The amount by which the specimen deforms is measured and expressed as millimeters (inches) of lateral expansion. Some standards for example require a lateral expansion of 0.38 mm for bolting materials and steels with a UTS exceeding 656 MPa, rather than specifying an impact value.

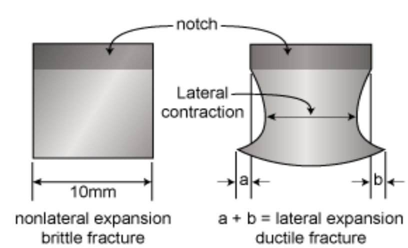


Figure 4. Lateral expansion measurements.

Industrial Use of Charpy Impact Test

The Charpy impact test can be used to assess the relative fracture toughness of different materials, e.g. steel and aluminum, as a tool for materials selection in design. It may also be used for quality control, to ensure that the material being produced reaches a minimum specified toughness level.
Difficulties arise when you attempt to answer questions such as "What impact toughness must my steel have if I'm to make an oil rig which will be subjected to wave impact in the North Sea at sub-zero temperatures?" Design problems such as this can be tackled by the use of minimum impact energy for the service temperature, which is based on previous experience. For example, it was found that fractures of the steel plate in Liberty ships in the 1940's only occurred at sea temperatures for which the impact energy of the steel was 20 J. This data was used to select steels for future ship designs. This approach is often still used to specify minimum impact energy for material selection, though the criteria are also based on correlations with fracture mechanics measurements and calculations. It's interesting to note that the impact energy of steel recovered from the Titanic was found to be very low (brittle) at -1ºC. This was the estimated sea temperature at the time of the iceberg impact.

Lab Procedure

Safety: all personnel are required to wear safety glasses at all time in this lab.

Apparatus

An impact testing machine (Model# 148725, Tinius-Olsen) with data acquisition module (T.O. Model Impact 104) will be used in this lab. It has the following specifications:
Pendulum capacity, J (ft.lb): 406 (300)
Drop height, m (ft): 1.5 (5)
Pendulum weight, kg (lb): 27 (60)
Impact velocity, m/s (ft/s): 5.5 (18)
Machine weight, kg (lb): 736 (1620)

Figure 5. Tinius Olsen impact tester and control computer.

Samples

The samples are machined according to ASTM E23 to a bar shape 55 mm with a 10 x 10 mm cross section and a V-notch at the center. The dimensions of the samples and a sample picture are shown in Fig. 6.

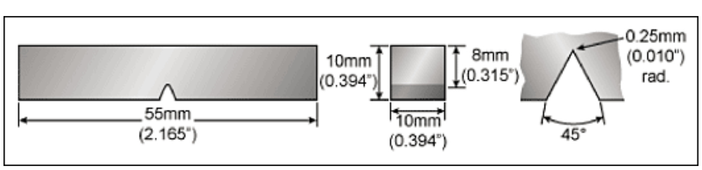


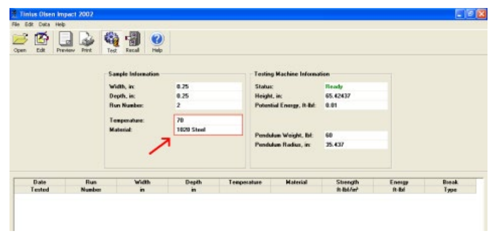
Figure 6. Charpy impact sample.

Testing

A. Preparation

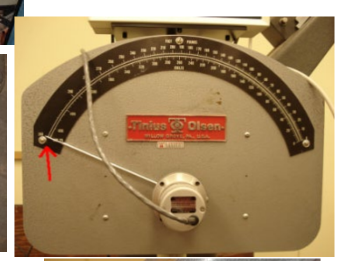
1. Prepare **hot water, icy water, and dry ice** with secured containers.
2. Place samples in the above mentioned containers. The samples should be kept in the media for at least 10 minutes before testing.
3. Turn on computer (Dell Solids Lab # 1) and login to the "Solids Lab # 1" profile.

4. Plug in the "Impact" software USB key into any USB port.
5. Connect the computer to the impact testing machine's data acquisition module using the RS232 serial cable.

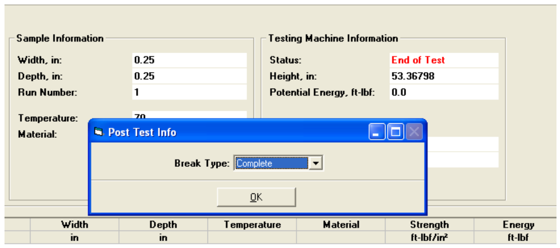


B. Charpy Test

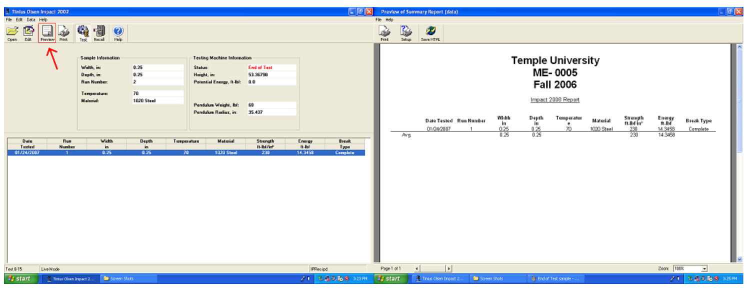
1. Turn on the Data Acquisition Module.
2. Double-click the "Impact" icon to run the impact testing software.
3. Take out a test sample and measure its temperature.
4. Enter the material's temperature in the "Sample Information" slots provided.
5. Check the Data Acquisition Module's screen and the software for a "Ready" status.
6. Lift and latch pendulum into position and close the safety latch to prevent latch handle from accidentally being released.
7. Place the Charpy sample as a simple beam in the test position. Note that the V-notch must face away from the pendulum hammer.
8. Set the force indicator needle to 300 lbf (406.7 J).
9. **Make sure there are no cables or other objects in the path of the pendulum hammer, also stand clear yourself!**
10. Unlatch the safety latch and pull the release lever.



11. After the sample is hit by the hammer use the "Brake" button to stop the pendulums motion.
12. Locate and pick up the test sample and any pieces and observe the fracture surfaces.
13. Take and save good quality photographs of the fracture surface. You will need to use them for determining the percentage of brittle fracture versus ductile.



14. Determine the *Break Type* in the software according to your observation.
15. Click on "Preview" to view data and print. You may also record the data given in your lab journal if printing is not available.



Absorbed energy values above 80 % of the scale range are inaccurate and shall be reported as approximate. Ideally an impact test would be conducted at a constant impact velocity. In a pendulum-type test, the velocity decreases as the fracture progresses. For specimens that have impact energies approaching 80 % of the capacity of the pendulum, the velocity of the pendulum decreases (to about 45 % of the initial velocity) during fracture to the point that accurate impact energies are no longer obtained.

16. Take lateral expansion measurements. One half of a broken specimen may include the maximum expansion for both sides, one side only, or neither. Therefore, the expansion on each side of each specimen half must be measured relative to the plane defined by the undeformed portion on the side of the specimen

You must collect both sides (broken halves) of the specimen and safe them for the following Labs. Keep each material in a separate compartment.

Repeat steps 3 – 16 for all samples.

C. Post Testing

1. Exit the impact software and shut off the computer.
2. Turn off the Data Acquisition Module on the impact test machine.
3. Unplug the RS232 serial cable, from both computer and test machine, and neatly roll it up.
4. Unplug the impact test machine from the AC power outlets.
5. Clean up any debris left over from testing.
6. Return computer station and any other equipment to its proper location.

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Requirements for the Lab Report (group report)

Content of "**Objectives**" and "**Methods and Materials**" is described in the file "Guidelines-Requirements_...".

"**Experimental Results and Data Analysis**" must include

1. The raw data and calculated parameters should be filled in the Table and be included in your report. A sample data sheet is attached at the end of the lab manual. An excel spreadsheet for the data is located next to the Lab manual on Canvas.
2. Show sample calculations for at least one analysis item which is to be entered into the data sheet.
3. For each temperature, plot the impact energy loss (impact resistance) versus carbon concentration curve.
4. For each material, plot the impact energy loss versus temperature. Determined the ductile to brittle transition temperature (DBTT) if it took place.
5. Present the photographs of the fractured surfaces and assess the percentage of crystallinity.
6. Present the lateral expansion measured either in mm or inch and its percentage in respect to initial width of the specimen.

Summarize your measurements in the table with calculated average and standard deviation, where it's appropriate.

"**Discussion**" must include:

- Discuss the effect of temperature on the impact energy loss for each type of steels and relate this to the material crystal structure.
- Reference to the photographs shown in the "Experimental Results" section and discuss the nature of fracture based on their appearance.
- Combine this discussion with the analysis of the lateral expansion data and their relation to material composition and temperature of measurements.

Discussion of any uncertainties, calibration, operator bias etc. is very welcome.

In **"Conclusion"** you shortly repeat the conclusions that you formulated in the "Discussion" and summarize the results and analyses that supported them. Other comments regarding the overall Lab is also welcome here.

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EXAMPLE DATA SHEET

Steel 1018							
	Impact Energy Loss, J	Initial Width, mm	Initial Thickness, mm	Final Width, mm	Final Thickness, mm	Lateral Expansion, %	Impact Strength, J/m^2
100 °C							
Test 1							
Test 1							
Test 3							
Test 4							
Test 5							
AVG							
STD							
22 °C							
Test 1							
Test 1							
Test 3							
Test 4							
Test 5							
AVG							
STD							
0 °C							
Test 1							
Test 1							
Test 3							
Test 4							
Test 5							
AVG							
STD							
-78 °C							
Test 1							
Test 1							
Test 3							
Test 4							
Test 5							
AVG							
STD							