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ME 241 Materials Laboratory

Ductile to Brittle Transition

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Objective

The purpose of the Ductile to Brittle Transition experiment is to analyze the ductile to brittle transition of two sample materials at three different temperatures. The two materials of interest are 304 Stainless Steel and 1018 Steel. The test will consist of using the Charpy Impact tester. Based on the results of the experiment, the transition temperature causing the specimens to either become brittle and fracture or to resist the force of the pendulum will be identified.

According to company requirements, the sample material needs to be able to operate at subzero temperatures. A suitable material should have an impact energy greater than 40 ft-lb within a temperature range of 32 and -108.4 °F. The structure of the crystalline lattice in the metals vary in the purity and on the concentration of carbides. “Carbides in steel, a certain amount of plastic deformation in the matrix is needed to initiate cracking or decohesion” [1]. A notch on the specimen is added for the purpose of initiating cracking. The temperature of the specimen does not affect the behavior of the notch because the cleavage fractures’ tensile stress is independent of the temperature.

The Charpy test can be used to check embrittlement monitoring of the steel upon undergoing a transition temperature. It can also be used for quality control specification purposes. During testing, “The specimen is broken by a pendulum, and the energy absorbed in fracture is obtained from the difference in height of the pendulum mass, before release, and when it comes to rest after breaking the specimen” **Error! Reference source not found..** The stress is dependent of the loading fixture and of the force of impact. Crack Arrest Temperature (CAT), which are the values of the measure in the closest to breaking point from materials testing on fracture mechanics, are useful for any engineering design. Someone designing a machine or even airplane can use these values to avoid any crack initiation or to limit a risk of fracture.

“Improvements have been made in the (ductile) fracture toughness of specific alloys by identifying the particles responsible for void growth and eliminating their effect by changes in alloy content or manufacturing practice.” **Error! Reference source not found..** “Fracture mechanics toughness values allow a quantitative safety analysis of steel structures” [1]. Due to results from fracture mechanics, a plane strain analysis can be made to simply predict the model of the ductile-brittle transition. Although during this experiment, this will be done after gathering all experimental results; “The plane strain analyses have shown that the model predicts the well-known ductile-brittle transition, with high absorbed energies at temperatures above the transition temperature and with low absorbed energies in the brittle range at lower temperatures” **Error! Reference source not found..** Based on the predicted behavior of the metallic properties for a low carbon steel, the dry ice temperature will get the material to exhibit a fast cleavage failure(fracture). Upon the fracture of the six samples, the flat surfaces of the fracture side on the material will show a shiny appearance and a bit reflective. This is a result from when “the cleavage crack passes from one grain to another of different orientations, it will change direction to continue propagation along the preferred crystallographic plane” **Error! Reference source not found..** So, one line of fracture might lead to a branch of new fractures, and so on, which explains the appearance on the specimen’s wall of fracture.

There are three ductile-brittle transition weakness factors known for low-strength steels; The triaxiality of stress, (which is also referred to as an invariant of stress and is the mean stress divided by the equivalent stress), a high strain rate, and low temperatures.

Experimental Equipment

This experiment required the use of the Charpy Impact Tester, safety goggles, tongs, a small pot and heater, cup of water and ice, dry ice as well as the 6 samples. Three of the six samples were 304 stainless steel and the other three samples were low carbon steel 1018.

Procedure and Observations

Prior to beginning the experiment, ensure that all the equipment discussed in Experimental Equipment section is properly setup. Additionally, ensure that all participants are wearing proper PPE and keep a safe distance from the Charpy Impact tester while in use.

Procedure:

1. Place one of each sample material into the ice bath, on the dry ice, and into the small pot.
2. Place the small pot on top of the heater and turn the heater on so that the water comes to a boil.
3. Wait about 15 minutes for the samples to cool down or heat up. The samples are expected to be approximately:
 - a. Dry ice (-78.8°C / -108.4°F)
 - b. Ice water (0°C / 32°F)
 - c. Hot water (100°C / 212°F)
4. Carefully place the sample into the fixture, using tongs.
 - a. Ensure that the notch is facing the side of impact.
5. Lift the arm towards the safety latch and clip the winch to the arm. Use the winch to raise the hammer to the safety latch. Ensure that the safety latch is holding the arm up and detach arm from the winch.

6. Move the dial indicator to the 264-ft-lb mark.
7. Ensure that all participants are not within range of the arm and release the arm, allowing the arm to swing and impact the specimen.
8. Record the value on the dial indicator.
9. Collect the fractures specimen(s) and take note of the fracture shape.
10. Repeat steps 2-9 for each sample.

Data & Results

The data acquired through experimentation can be seen in Table 1. This table details the material, temperature regime which the material was put in to reach the desired temperature, the impact energy in both lb.-ft and J, as well as whether the material experienced complete or incomplete fracture. The impact energy in Joules (J) was a calculated result from Equation 1, using the fact that 1 lb.-ft is equivalent to 1.35582 J (See Appendix A for Sample Calculations). The new deviation was calculated using Equation 2 [4]. The impact energy was plotted as a function of temperature in Figure 1.

$$ImpactEnergy_J = ImpactEnergy_{lb.-ft} * 1.35582 \frac{J}{lb.-ft}$$

Equation 1

$$\delta q = |B| \delta x$$

Equation 2

Table 1: Experimental Results

Material	Temperature Bath	Impact Energy (ft-lb)	Impact Energy (J)	Complete Fracture
		$E \pm \delta$	$E \pm \delta$	(Yes or No)

304 Stainless Steel	Dry Ice	129 ± 3	174.90078 ± 4.07	Yes
304 Stainless Steel	Ice Water	119 ± 3	161.34258 ± 4.07	Yes
304 Stainless Steel	Boiling Water	116.5 ± 3	157.95303 ± 4.07	No
1018 Steel	Dry Ice	15.5 ± 3	21.01521 ± 4.07	Yes
1018 Steel	Ice Water	67.5 ± 3	91.51785 ± 4.07	No
1018 Steel	Boiling Water	49.5 ± 3	67.11309 ± 4.07	Yes

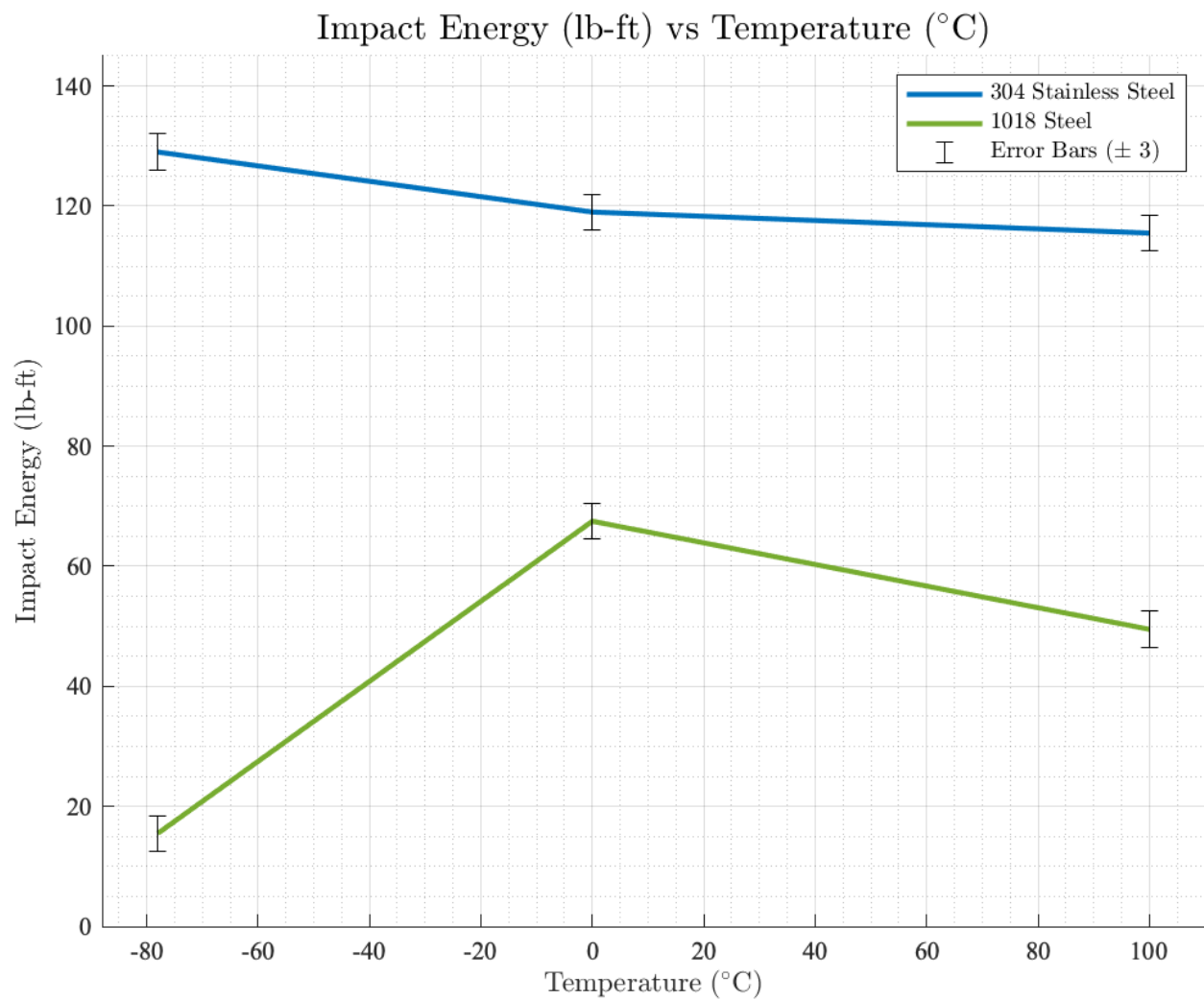


Figure 1: Plot of Impact Energy vs. Temperature for Sample Materials

Figure 2 pictures all the specimens after the impact test.

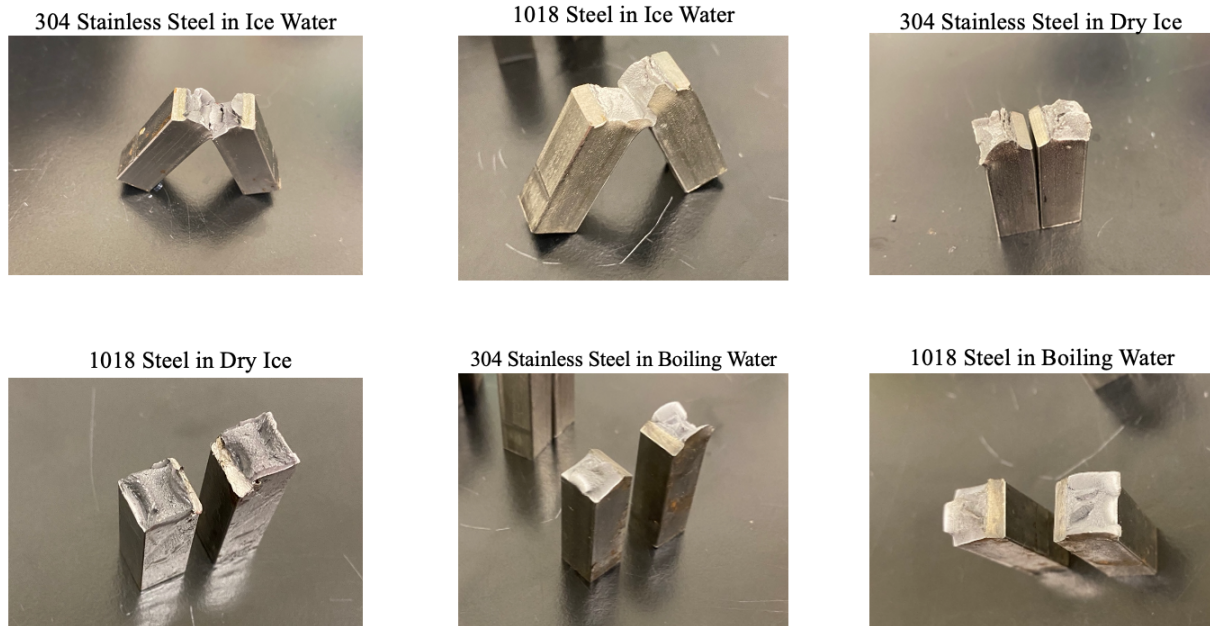


Figure 2: Samples After Impact Test

Discussion of Results

Based on Figure 1, the 1018 steel experienced ductile behavior at higher temperatures and brittle behavior at lower temperatures. This is evident since the impact energy of the sample acclimated to dry ice had a significantly lower impact energy than that of the samples acclimated to ice water and boiling water. The 304 stainless steel on the other hand did not show any significant changes in impact energy for the samples in different temperature regimes. It maintained relatively constant values of impact energy.

This means that the 304 stainless steel does not experience a ductile to brittle transition, at least in the temperature range that was tested in this experiment. The 1018 steel did experience a ductile to brittle transition; however, the temperature range tested does not provide enough data to estimate the temperature at which that occurs.

One distinct difference between the 304 Stainless Steel and the 1018 Steel is their crystal structures. This material property affects the manner in which the material reacts to changes in temperature. The results show that the ability to absorb energy for the 1018 steel, which has a BCC crystal structure, was significantly influenced by temperature. On the other hand, the impact energy of the 304 Stainless Steel, which has a FCC crystal structure, was only slightly affected by changes in temperature.

Although there was an evident change in impact energy for the 1018 steel and steady values for the 304 stainless steel, there is not enough data to come to a meaningful conclusion about the results. Firstly, there is a good amount of experimental error present. The primary source of error is acclimating the samples to the different temperature regimes. Due to non-ideal conditions in the lab, it was very difficult to place the sample in the three different temperature baths for 15 minutes. Failure to place the samples in the temperature baths for 15 minutes would have a direct effect on the impact energy they experience. Secondly, when testing the ductile to brittle transition temperature, it is vital to complete the test within five seconds of the sample being removed from the temperature bath. For many of the trials, the sample was exposed to room temperature for more than five seconds before impact, meaning that the sample attempted to reach equilibrium by either cooling for the boiling water sample, or warming up for the dry ice and ice water samples. This is due to a simple principle of thermodynamics, stating that materials always seek thermodynamic equilibrium, which rids the samples of any temperature gradients. These two factors are the primary sources for experimental error.

One approach that would have accounted for this would be to complete multiple trials for each run. Increasing the sample size of a test allows for a more accurate reading to be acquired. Since this lab experiment only allowed time to obtain one data point for each material at each

temperature, all error is present in the data. Having multiple runs and taking the average would have resulted in more accurate data.

Conclusion

The results from the ductile to brittle lab can be seen in our history's past. The sinking of the titanic relates to our lab. A ductile to brittle test could have been used to see that the steel of the ship became very brittle in icy water. In the conditions the ship was travelling, even the smallest impact could have created a large amount of damage. The ductile to brittle test can be useful for everyday life and help prevent major accidents.

Based on the findings 304 stainless steel would meet the company's minimum requirement of 40 ft-lb between the temperatures of 32- and 108.4-degrees Fahrenheit. 1018 steel became brittle under these conditions especially when it was exposed to very cold temperatures. This is because of their crystalline structure. Under certain temperatures the atoms are moving in diverse ways, it could be strong under plenty of heat or weak when it is exposed to the cold. It would be advised to choose the 304 stainless steel for the application because it passed the company's requirements under all temperatures while 1018 steel failed only under freezing temperature.

Appendices

Appendix A

Sample Calculations

Impact Energy in Joules:

$$ImpactEnergy_J = ImpactEnergy_{lb.-ft} * 1.35582 \frac{J}{lb.-ft}$$

$$ImpactEnergy_J = 129 \text{ lb.-ft} * 1.35582 \frac{J}{lb.-ft}$$

$$ImpactEnergy_J = 174.9 \text{ J}$$

New Deviation for Impact Energy in Joules:

$$\delta q = | B | \delta x$$

$$\delta ImpactEnergy_J = | 1.35582 | * 3$$

$$\delta ImpactEnergy_J = 4.07$$

Appendix B

MATLAB CODE

```
close all; clear
```

Data

```
% Temperature (deg C)
temperature = ([-108.4 32 212] - 32) * 5/9;

% Impact Energy for 304 Stainless Steel (ft-lb)
impactEnergy304 = [129 119 115.5];

% Impact Energy for 1018 Steel (ft-lb)
impactEnergy1018 = [15.5 67.5 49.5];
```

Plots

```
% Creating New Figure
figure(1)

% Keeps figure one
hold on
% Turns grid on
grid on
% Makes grid size sma;;
grid minor

% Plotting temperature versus impact energy for 304 stainless steel
plot(temperature, impactEnergy304, 'Color', '#0072BD', 'LineWidth', 2);

% Plotting temperature versus impact energy for 1018 steel
plot(temperature, impactEnergy1018, 'Color', '#77AC30', 'LineWidth', 2);

% Setting Axis Limits
xlim([-88 110]);
ylim([0 145]);

% ----- Error Bars -----

% Defines error as 3
deltaImpactEnergy = 3;
% Creating error vector
error = deltaImpactEnergy * ones(size(impactEnergy304));
% Plotting error Bars
errorBar304 = errorbar(temperature, impactEnergy304, error);
errorBar1018 = errorbar(temperature, impactEnergy1018, error);
% Modifying error bar properties
errorBar304.Color = 'k';
errorBar304.CapSize = 5;
errorBar304.LineStyle = 'None';
errorBar1018.Color = 'k';
errorBar1018.CapSize = 5;
errorBar1018.LineStyle = 'None';

% ----- Plot Descriptors -----

% Creates Y-Axis Label
ylabel(' {Impact Energy (lb-ft)}', 'fontsize', 11, 'FontName', 'Times', ...
    'Interpreter', 'latex');
% Creates X-Axis Label
```

```

xlabel(' {Temperature ($$\wedge\circ$$C)}', 'fontsize', 11, 'FontName', 'Times', ...
      'Interpreter', 'latex');
% Creates Plot Title
title('{Impact Energy (lb-ft) vs Temperature ($$\wedge\circ$$C)}', 'fontsize', 14, ...
      'FontName', 'Times', 'Interpreter', 'latex');
% Generates and positions legend
legend('304 Stainless Steel', '1018 Steel', 'Error Bars ($$\pm$$ 3)', 'location',
      ...
      'northeast', 'FontName', 'Times', 'Interpreter', 'latex');
% Adjusting Axis Properties
ax = gca;
ax.FontName = 'Times';

```

Calculations

```

% Converting impact energy from lb-ft to Joules
% 1 ft-lb = 1.35582 J
impactEnergy304J = impactEnergy304 * 1.35582;
impactEnergy1018J = impactEnergy1018 * 1.35582;
% Calculating the new error for conversion
deltaImpactEnergyJ = abs(1.35582) * deltaImpactEnergy;

```

References

- [1] Francois, D., & Pineau, A. (2002). *From Charpy to Present Impact Testing (Volume 30)* (*European Structural Integrity Society, Volume 30*) (1st ed.) [E-book]. Elsevier Science.
- [2] IAIN., D. C. (2018). *Finnie's notes on Fracture Mechanics: Fundamental and practical lessons*. SPRINGER.
- [3] Lab Manual (Camacho, 2021).
- [4] J. R. Taylor, “Principal Formulas in Part 1” in *An Introduction to Error Analysis: The Study of Uncertainties in Physical Measurements*, (University Science Books, 1996), Vol. 9, Chapter 3.