Analysis of Ductile to Brittle Transition Temperature

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Abstract: This experiment examined the effect of heat treatment on the microstructure of the steel. The purpose of this experiment is to find how the structure of different heat treatments on metals can affect the fracture behavior using the Charpy test to determine the ductile to a brittle transition temperature (DBTT). As a result, BCC shows more pronounced DBTT behavior than FCC material.

INTRODUCTION

Within this experiment, aluminum and various heat-treated steel samples are tested using the Charpy Test to explain the temperature transition from ductile to brittle fracture. Ductile to Brittle Transition Temperature (DBTT) is the minimum amount of energy that can be absorbed by a material before fracturing. When the temperature and energy data points are plotted, the transition temperature can be located when there is a stark increase in energy from a small change in temperature. Materials show ductile behavior at higher temperatures and absorb high impact energy whereas brittle fractures occur at lower temperatures and do not absorb a lot of energy from impact. As a result, brittle fractures occur rapidly with a clean break at the fractured surface but ductility allows the material to deform under a load so that when it fractures the surface has a necking point or elongation of the sample.

Each material has a different DBTT because of its dependency on the composition of that specific material. The most common arrangement of atoms is in body-centered cubic (BCC) formation or face-centered cubic (FCC). BCC unit cells contain a quarter of an atom on each corner on a cube and then a whole atom in the middle. For FCC unit cells the atoms on the corners are the same only accounting for a quarter of the atom seen in BCC but they have half of an atom on each face of the cube.

Charpy test (CVN) is employed to test impact fracture, the failure of material as stress is applied at a temperature below its melting point. For this experiment, various heat-treated plain carbon steels and aluminum samples are tested to see if they experience ductile-to-brittle-transition-temperature (DBTT) with decreasing temperature. Generally, the lower the impact energy, the more brittle the material will be because brittle material is strong - can withstand high force - but not tough - allows deformation - so that it usually absorbs less energy than ductile material before fracture.

BACKGROUND THEORY

<u>IMPACT FRACTURE</u>: the energy required before fracture.

<u>CHARPY TEST</u>: is most commonly used on metals to evaluate the relative toughness or impact toughness of materials. The Charpy impact test (also known as the Charpy V-notch test) is a high strain rate test that involves impacting a standard notched sample with a weight-controlled pendulum swinging from a set height. The impact test helps to measure the energy absorbed by the specimen during fracture. The standard Charpy-V notched sample has a length of 55mm, a 10mm square, and has a notch that is 2mm deep. The radius of the tip processed on one face is 0.25mm. This is particularly useful for ferritic steels that show a transition from toughness to brittleness as the temperature decreases. When conducting an impact test, brittle metals will absorb a small amount of energy, while tough ductile metals will absorb a large amount of energy. The appearance of the fracture surface can also provide information about the type of

fracture that has occurred. When reporting the results of the Charpy test, always report the energy absorbed (in J).

BEHAVIOR OF BCC AND FCC MATERIALS DURING IMPACT: only BCC metal shows obvious DBTT property as a result of temperature-dependent dislocation motion. That is because FCC has more slip systems that allow dislocation movement at all temperatures. BCC, on the contrary, does not have a close-packed plane. Thus, it needs thermal energy for the dislocation movement.

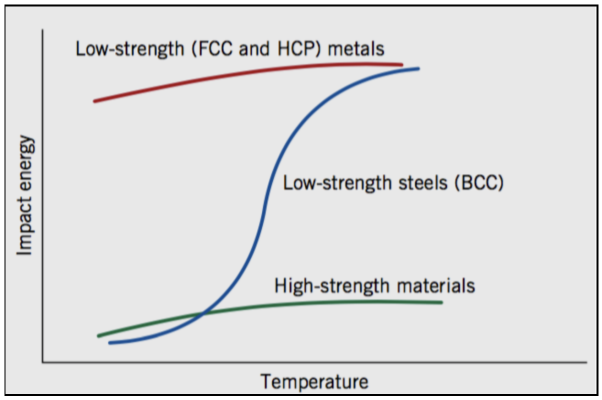

Figure 1*: The graph shows the relationship between impact energy and temperature of low-strength FCC metals, low-strength BCC steels, and high-strength materials.*

THEORETICAL ANALYSIS

What we used for measurement is a Charpy test, Usually, there will be a pendulum striking on a notched specimen and the amount of energy absorbed during fracture will be measured.

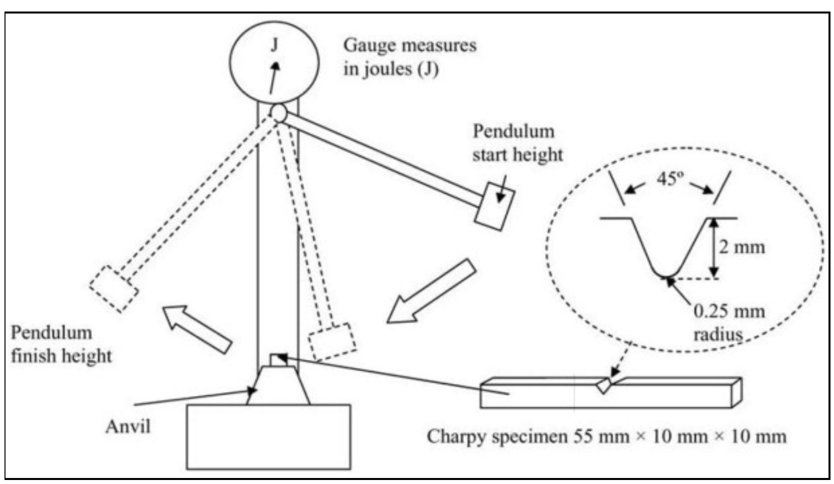

Figure 2: *How the Charpy test works (Steven, 2009)*

The first analysis is the impact energy of metals during the Charpy test. By quenching the samples heated at high temperatures in water and cooling to room temperature in a high-temperature furnace, two samples of the same material with different histories were obtained. Then go through the Charpy test twice, the impact energy of each sample is measured. With this step, it can be concluded that different cooling methods have different effects on the internal structure of the sample.

In the second part of the measurement, liquid nitrogen was used to cool all the remaining samples cooled in the high-temperature furnace. The liquid nitrogen will be removed and the sample temperature will gradually return to room temperature. During the temperature increase of the sample, after each temperature increase by a certain value, impact energy will be measured and recorded until the impact energy is close to the measured value at room temperature. Simultaneously repeat the above experiment on aluminum samples. Through the change of impact energy during the temperature increase, DBTT can be displayed on the temperature-impact energy curve.

PROCEDURE

In order to test the fracture behavior of metals, 1018 carbon steels: water quenched steel, air-cooled steel, and furnace cooled steel, and 6061 aluminum would be prepared. Steel samples were put in the furnace at 1000 °C for 3 hours and cooled in water, air, or furnace. Steel samples and aluminum samples would then be put into liquid nitrogen for 15 min. They will be taken out from liquid nitrogen to test impact fractures at different temperatures, from their initial temperature until resuming room temperature. During the Charpy test, samples would be locked securely. A Hammer would be aligned facing the notch and the indicator would be set to the highest energy level. After the hammer hit the sample and broke it. The amount of energy absorbed during fracture would be recorded.

RESULTS

Water Quenched Steel		**Air Cooled Steel**		**Furnace Cooled Steel**		**Aluminum**	
Temperature (°C)	Energy (ft/lbs)	Temperature (°C)	Energy (ft/lbs)	Temperature (°C)	Energy (ft/lbs)	Temperature (°C)	Energy (ft/lbs)
-24.8	5	-10.8	6	-12.4	5.5	-46.1	18
-4.2	4.5	-9.2	2.5	-11	6.5	-36.2	17.4
-2.7	7	-7.3	35	-4.9	7	-33.5	20.5
-0.5	5	-5.1	6	-1	13	-30	18.5
3.2	4.5	-4	21.5	-0.5	9.5	-20.3	18
3.7	26	-3.7	3.7	0.3	72	-17.5	5.5
3.7	19	-3.5	96	0.8	75	-15.1	17.3
3.8	19.5	-3.4	109	1.6	81	-13.1	21.5
3.9	39	-2.4	74	2.2	63	-10	16.8
4	59	-1.6	109	4.1	71	-6.6	19.2
4.3	92	-0.9	99.5	5.1	94	-4.3	16.5
5.5	71	-0.6	112	21.9	97.5	-3.7	18.2
12.4	121	-0.6	146	22	110	1.8	18
23.2	103	1.6	150	22.4	98	3.9	19.5
23.4	159	1.7	113			4.2	18.2
23.6	99	22	171			4.3	18
		22.1	138			8.2	18.6
		22.2	144			10.9	18.3
						13.5	19.4
						16	18.7
						21.9	21
						22.2	17.5
						22.2	18

Table 1: *Listed are the various materials tested using the Charpy Test. The amount of data for each sample varies due to the difference in temperature each was kept at.*

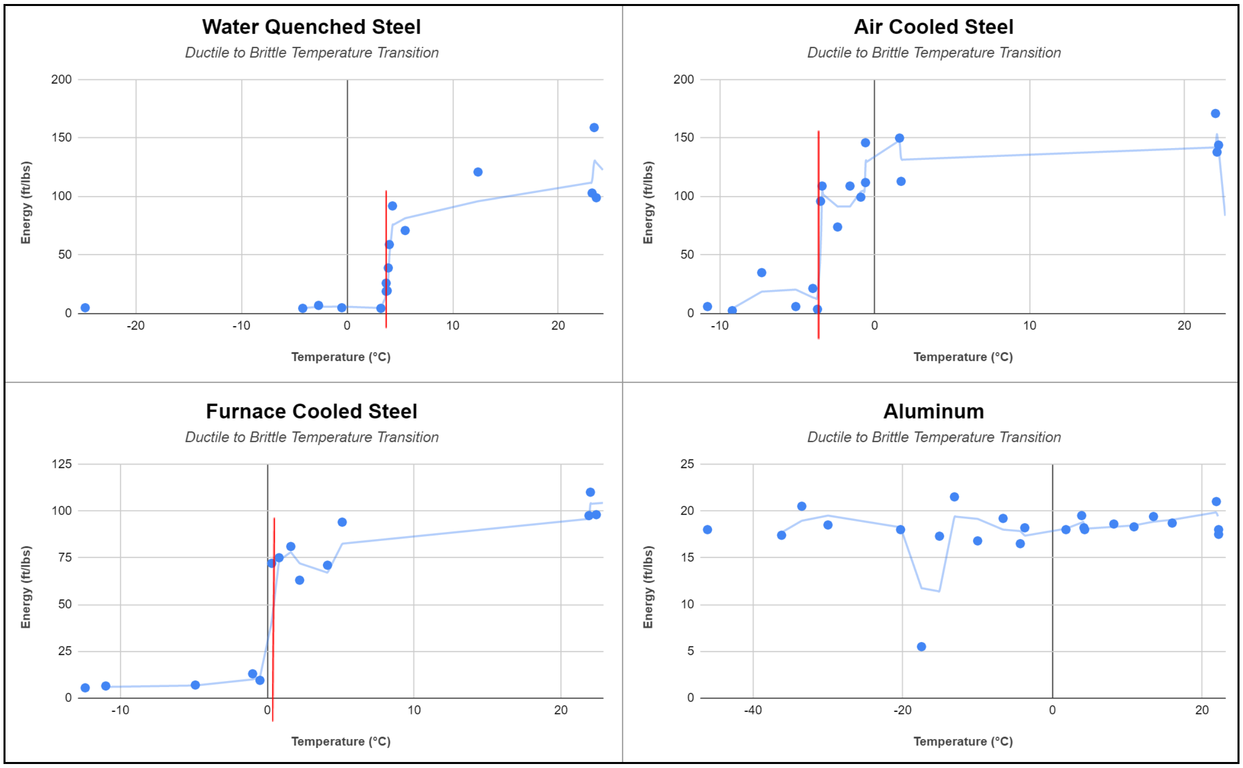

Figure 3: *Each data set is graphed respective to its own category of material. The red line shown is the transition temperature which is the average of the two temperatures associated with the energy change from low to high absorption levels. Comparing each graph, aluminum data does not follow the trend seen by the other three graphs as the higher temperature lowers the energy temporarily then continues to rise to its previous state.*

DISCUSSION

The overall flat distribution of energy across all temperatures for Aluminum in Figure 1 above can be interpreted such that Aluminum does not exhibit a ductile to brittle transition. This is due to this metal having an FCC crystal structure as opposed to the BCC structure found in steel.

The only difference between the three samples of 1018 steel is how quickly they were cooled. The steel that was cooled the fastest was the water quenched steel because water has the highest heat capacity among others which allows it to absorb heat faster. The water quenched steel has a martensitic microstructure, which is a body-centered tetragonal structure (BCT). The DBTT of water quenched steel was measured to be around 4 Celsius. The steel with the next fastest cooling rate is air-cooled steel. This steel becomes bainite and exhibits a DBTT of about -4 Celsius. The sample that was allowed to cool in the furnace had the lowest cooling rate. It turns into pearlite and has a DBTT of around 0 Celsius. As a result, the slower it cools, the more pearlite the steel will be like.

Theoretically, the faster the sample cooled, the less carbon will diffuse out and the higher DBTT it should obtain. However, furnace cooled steel shows a higher DBTT than air quenched. It might be because the carbon concentration in a furnace is higher than in the air. Thus, carbon may actually diffuse slower than air cool. In addition, grain size also plays a part in affecting the value of DBTT. The larger the grain size, the higher the DBTT, and the slower steel cools, the larger the grain size. As a result, furnace cooled steel gains a higher DBTT than air-cooled steel. Since the water quenched steel cools much faster than the other 2 samples, the effect of grain size can be ignored and it gains the highest DBTT as expected. If this trend persists and is statistically significant, further experimentation will include an SEM to examine the precise microstructure formed and how that microstructure alters the DBTT.

DISCUSSION QUESTIONS

1. In order to increase the DBTT of steel, the carbon concentration also needs to increase. By allowing more carbon into the steel's composition it becomes more brittle due to the carbon content deforming the lattice which raises the DBTT. In addition, increasing grain size can also increase DBTT (vice versa when the grain size is decreased, so is the DBTT).
2. Most polymers and ceramics will experience DBTT. For ceramics, because of their high stability, DBTT will happen at a much higher temperature than metals, usually more than 1000 °C. While for polymers, DBTT happens at a lower temperature than metals, around -100~ -20 °C.
3. No, Austenitic stainless steels will not undergo a transition from ductile to brittle because of their FCC structure being independent of temperature-related slip dislocations.
4. CTT diagram represents what phase can be formed at different cooling rates, while the phase diagram represents what physical property of a substance (solid, liquid, or gas phase) can be present at different pressures. Looking at a phase diagram of Fe_3-Fe_3C, the phase martensite is not present. Martensite is a body-centered tetragonal crystal that occurs when carbon is dissolved in iron during quenching which deforms the lattice sites at a rapid rate making martensite a metastable phase. All the other phases present on the diagram are equilibrium phases that occur from slow cooling rates allowing for sufficient diffusion and therefore since martensite counteracts this process, it's not present.
5. Oil quenched steel is expected to have lower DBTT than water quenched steel because oil has lower specific heat than water. Thus, steel in oil will cool slower which means steels will have more time to release carbon. In addition, less carbon concentration can also result in more ductile steel.

CONCLUSION

1018 Steel exhibits a ductile to brittle transition temperature at approximately zero Celsius for all heat treatments. The Aluminum does not exhibit this behavior.

It is possible that the difference in DBTT values across the three samples of steel is within some unknown margin of error and is therefore statistically insignificant and no conclusion can be reached.

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