Ductile and Brittle Fracture of 1018 Steel and

304 Stainless Steel Using Charpy Impact Test

Eman Mousa Alhajji

North Carolina State University

Department of Materials Science and Engineering

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Siddharth Gupta

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Abstract

The objective of this experiment was to use Charpy impact testing to demonstrate how temperature and the crystal structure (FCC versus BCC) of a metal can significantly influence the metal's ability to plastically deform and absorb energy during impact fracture. Using S1-1D SATEC systems impact tester, 1018 Steel and 304 Stainless Steel were examined at – 196 ºC, - 78 ºC, 0 ºC, 24 ºC and 100 ºC. Optical micrograph representative of the fracture surface at the extreme test temperatures were taken by ZEISS Stemi 2000-c stereo microscope. The average impact energy measured at 100 ºC was 282.01 ± 3.58 J for BCC 1018 steel and 178.51 ± 15.65 J for FCC 304 steel. Furthermore, the average impact energy measured at -196 ºC was 2.25 ± 3.58 J for BCC 1018 steel and 104.85 ±15.71 J for FCC 304 stainless steel. The impact energy vs. temperature curves showed that The average impact energy measured at 100 ºC was 282.01 ± 3.58 J for BCC 1018 steel and 178.51 ± 15.65 J for FCC 304 steel. Furthermore, the average impact energy measured at -196 ºC was 2.25 ± 3.58 J for BCC 1018 steel and 104.85 ±15.71 J for FCC 304 stainless steel. FCC 304 stainless steel did not have ductile to brittle transition whereas BCC 1018 steel was determined to have a ductile to brittle transition temperature of about -101 ºC. The experiment implies that when materials are cooled below their DBTT, they suddenly lose ductility and become brittle, fracturing without any warning. Because DBTT can be changed by changes in microstructure and composition, DBTT is not considered a material constant.

Introduction

Fracture is defined as the separation of a material into pieces due to an applied stress. Based on the ability of materials to undergo plastic deformation before the fracture, two types of fracture can be observed: ductile and brittle fracture. [1,2] In ductile fracture, materials have extensive plastic deformation and energy absorption before fracture, resulting in slow progression of a crack over time. In contrast, materials with brittle fracture show relatively little plastic deformation and low energy absorption before fracture, resulting in a rabid propagation of a crack. [2] A ductile fracture introduces a significant change in shape of the test sample around the area of the notch and the fracture surfaces will be jagged and irregular in appearance. A brittle fracture causes little or no change in shape of the test sample around the area of the notch and the fracture surface appears flat and shiny. [1,2]

The ability of materials to undergo plastic deformation and absorb energy can vary widely depending on variables such as alloy composition, crystal structure, processing and environmental conditions such as temperature. As temperature decreases, a ductile material, such as a BCC metal, can become brittle. BCC metals are not closed back; therefore, thermal activation is needed in order for dislocations to pass one another and plasticity deform. However, FCC metals have more active slip systems that are insensitive to temperature due to their atoms being closed packed. Thus, materials with FCC crustal structure stay ductile even at low temperature, as illustrated in Figure 1. In BCC metals and other materials, the impact energy needed for fracture drops suddenly over a relatively narrow temperature range, which is defined as the ductile-brittle transition temperature (DBTT). DBTT is an important parameter in selecting materials that are subjected to mechanical stresses since it defines the tendency to suddenly break instead of bending or deforming. High strain rates, low temperatures cause the DBTT to increase. [1] Furthermore, the presence of a notch, which causes a triaxisl stress state, causes the DBTT to increase. [1]

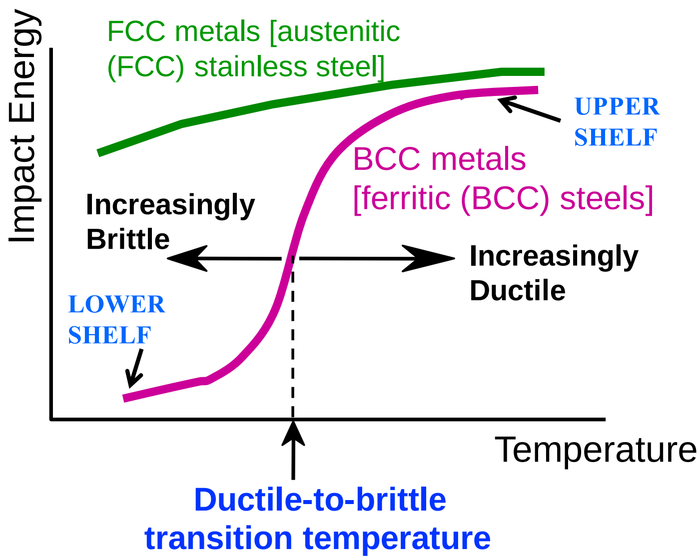


Figure 1. DBTT curves for typical FCC stainless steels and BCC steels. [1]

One of the useful technique used in materials science and engineering to determine fracture characteristics is Charpy impact test. [1,2] Charpy impact test is designed to measure the impact toughness, the energy absorbed, during fracture at a high strain rate as a function of temperature. In the analysis of ductile to brittle transformation, fracture toughness measurements are more critical than tensile strength measurements. Fracture toughness defines the ability of a material to resist fracture through plastic deformation whereas tensile strength defines the ability of a material to withstand external stress without breaking. The Charpy technique uses a notched sample and a hammer to determine the energy needed to fracture the sample, as shown in Figure 2.

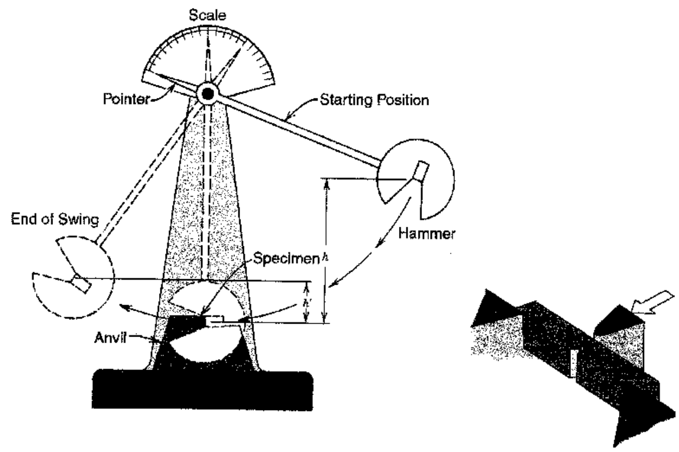


Figure 2. Schematic of Charpy impact tester. [1]

The presence of the notch in the specimen and the almost rapid nature of the loading increase the harshness of the test. The stress concentration at the base of the notch initiates the crack which propagates in a specific direction with slight plastic movement. Since it is difficult to analyze the complex triaxial stress state created by the notch in the specimen, the results obtained can only be considered qualitatively for engineering design specifications. [1,2]

The DBTT can be estimated at the temperature correlating with the impact energy value calculated by:

$$\mathrm{LSE} + \frac{\mathrm{USE}-\mathrm{LSE}}{2} \tag{1}$$

where LSE us the lower shelf energy and USE is the upper shelf energy. The slandered deviation is given by:

$$S_N = \sqrt{\frac{1}{N}\sum_{i=1}^{N}(x_i - x_{ave})^2} \tag{2}$$

where S_N is the slandered deviation , N is the number of data and x_{ave} is the average, which is the sum of data divided by the number of the elements in the data. [1]

The objective of this experiment was to use Charpy impact testing to demonstrate how temperature and the crystal structure (FCC versus BCC) of a metal can significantly influence the metal's ability to plastically deform and absorb energy during impact fracture. Using S1-1D SATEC systems impact tester, 1018 Steel and 304 Stainless Steel were examined at – 196 ºC, - 78 ºC, 0 ºC, 24 ºC and 100 ºC.

Experimental procedure

In this experiment, the equipment used for measuring the impact energy was S1-1D SATEC Systems Charpy impact tester. The equipment used for observing the fracture surface was ZEISS Stemi 2000-c stereo microscope. The samples examined were 55mm long by 10 mm square bars of annealed 1018 steel and 304 stainless steel. Each bar had a 2 mm deep 45-degree V-shaped notch (0.25 mm root radius) in the center of one face. The annealed 1018 steel samples were composed of iron with 0.18% C, 0.8% Mn, and 0.4% Si and had a BCC crystal structure and ferrite and pearlite microstructure. The 304 stainless steel samples were composed of iron with 18% Cr and 9% Ni and had a FCC crystal structure and austenite equiaxed grain microstructure. The samples were tested at – 196 ºC (liquid nitrogen), - 78 ºC (dry ice with isopropyl alcohol), 0 ºC (ice and water), 22 ºC (room temperature) and 100 ºC (boiling water). The experiment was performed at a pressure of 1 atm.

Three samples of each material were obtained to be tested at each temperature. For each sample, the following steps were performed to run the Charpy impact test. First, the hammer was lifted up till it locked in place at the upper position. Then, the pointer was set to 240 ft-lbs (325.4 J), which was the potential energy of the hammer in the upper position. Using tongs, the Charpy sample was placed with the notch facing away from hammer. In addition to placing the tongs in the same medium of each sample prior to preforming the impact test, transformation of the sample was done as quickly as possible using the 5 second rule to avoid any significant change in the sample's temperature. After the area was assured to be clear, the hammer was released using the latch mechanism. Once the sample was broken, the latch was moved to the brake position to stop movement of the hammer. The data was record and the overall shape of each specimen was visually examined to classify the type of fracture.

Using the stereo microscope, the fracture surface of one sample of each of the four following combinations: 1018 steel at 100 ºC and -196 ºC and 304 stainless steel at 100 ºC and -196 ºC, was inspected. Optical micrograph representative of the fracture surface was taken for each sample.

Results and Discussion

Based on the data collected using the Charpy impact tester, the fracture type, the average impact energy and standard deviation values of each three sample data set were determined and summarized in Table 1. As a sample calculation, the average impact energy of BCC 1018 steel and the slandered deviation at -196 ºC were found as following:

$$x_{ave} = \frac{2.711 + 2.711 + 1.355}{3} = 2.259 \text{ J}$$

$$S_N = \sqrt{\frac{1}{3}\left((2.711 - 2.259)^2 + (2.711 - 2.259)^2 + (1.355 - 2.259)^2\right)} = \pm 0.782.$$

The average impact energy measured at 100 ºC was determiend to be 282.01 ± 3.58 J for BCC 1018 steel and 178.51 ± 15.65 J for FCC 304 steel. Moreover, the average impact energy measured at -196 ºC was determined to be 2.25 ± 3.58 J for BCC 1018 steel and 104.85 ±15.71 J for FCC 304 stainless steel. It was generally observed that as temperature decreased, the impact energy decreased. Measurements above -78 ºC showed that BCC 1018 steel samples absorbed more impact energy than FCC 304 steel samples. At liquid nitrogen temperature (-196 ºC), the impact energy measured for FCC 304 steel was significantly higher than the impact energy measured for BCC 1018 steel. A rapid decrease in the impact energy was detected for BCC 1018 steel between -78 ºC and -196 ºC. It was also found that the BCC 1018 steel samples measured at -196 ºC had a brittle fracture. However, no rapid decrease in impact energy was detected for FCC 304 stainless steel.

Table 1. The average impact energy and fracture type for FCC 304 steel and BCC 1018 steel.

Temperature (ºC)	**Impact Energy of BCC 1018 Steel**	**Fracture**	**Impact Energy of FCC 304 Steel**	**Fracture**
-196	2.25 ± 3.58	Brittle	104.85 ±15.71	Ductile
-78	172.19 ± 4.06	Ductile	141.46 ± 11.04	Ductile
0	279.75 ± 18.05	Ductile	130.15 ± 14.35	Ductile
22	277.49 ± 6.82	Ductile	127.44 ±7.17	Ductile
100	282.01 ± 3.58	Ductile	178.51 ± 15.65	Ductile

The absorbed impact energy was plotted as a function of temperature for BCC 1018 steel and FCC 304 stainless steel as shown in Figure 3. The BCC 1018 steel curve presented a changes in fracture behavior from ductile at high temperature to brittle at low temperature. However, the FCC 304 stainless steel curve, showed an approximately steady values of the absorbed impact energy at high and low temperatures.

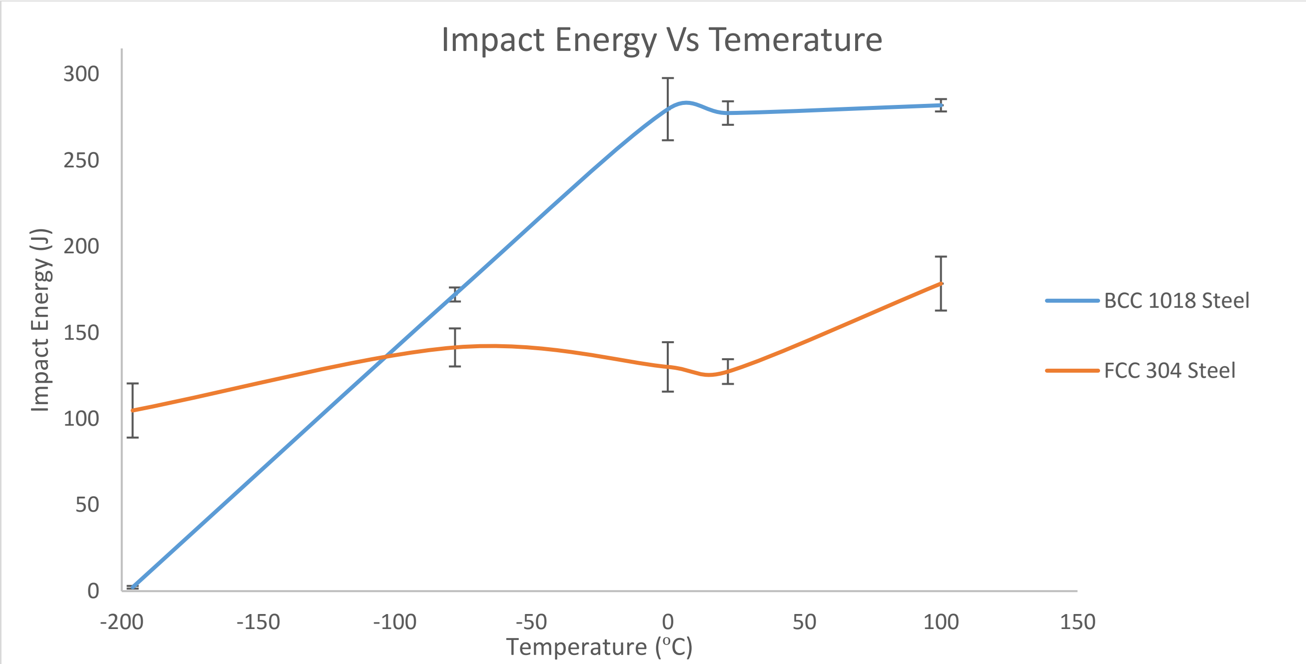


Figure 3. Impact energy verses temperature curves for BCC 1018 steel and FCC 304 stainless steel.

Results showed that steels with an BCC crystal structure suffer from ductile-to-brittle transformation whereas stainless steels with an FCC crystal structure do not. An estimate of the DBTT of BCC 1018 steel was determined as following:

$$2.25 + \frac{282.01 - 2.25}{2} = 142.13 \text{ J}.$$

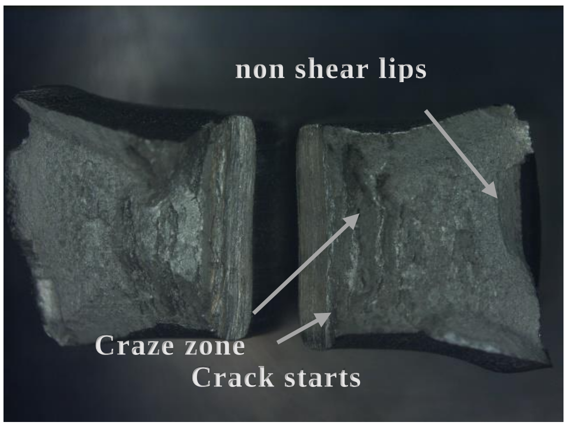
Using Figure 3 and the result obtained from Equation 2, this impact energy was found to correspond to a temperature of about -101 ºC.

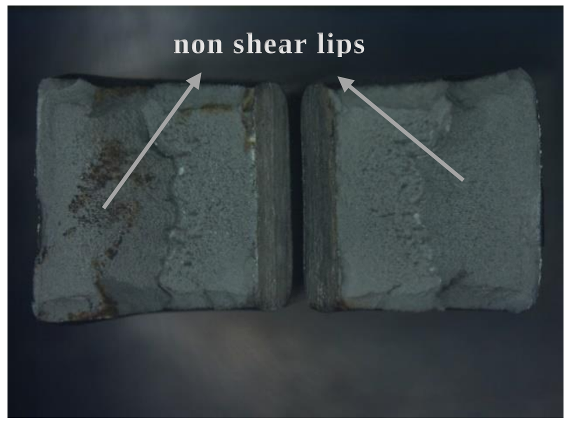
The experimental results showed that materials ability to absorb energy increases with the increase in temperature. It was also found that decreasing temperature has a significant influence on the ability of (BCC) ferritic 1018 steel to absorb energy before failure whereas decreasing temperature has a limited influence on the ability of (FCC) austenitic 304 stainless steel to absorb energy. Such phenomena can be explained by the fundamentals of crystallography and the motion of dislocations related to thermal activation. As temperature increases, the vibration of atoms increases, which allows the atoms under stress to slip to new planes more easily. [1,2] BCC 1018 steel samples were found to be brittle at lower temperature because metals with BCC crystal structure are not closed packed and require thermal activation in order for the material to plastically deform. Therefore, the motion of dislocations in BCC metals becomes significantly difficult or nearly impossible below -101 ºC, resulting in a brittle failure. [1] On the other hand, because FCC is closed packed, dislocation slip is not temperature sensitive, resulting in an absence of a DBTT in FCC 304 stainless steel. [1]

The presence of the notch in the steel specimens increased the intensity of the impact test. The stress concentration at the base of the notch initiated the crack to propagate in a specific direction with small plastic flow. Since it is difficult to analyze the complex triaxial stress state created by the notch in the specimen, the results obtained were not considered for engineering design specifications. [1,2]

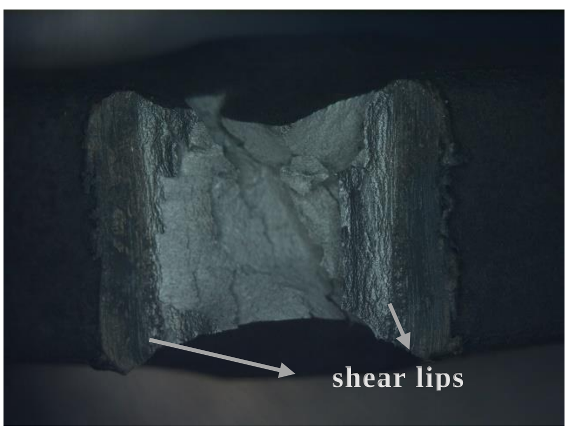
When compared to the literature results shown in Figure 1, the general trends obtained experimentally agree with the literature findings. FCC steels do not experience ductile to brittle temperature transformation while BCC steels do. [1,2,3] However, the literature results showed that FCC 304 stainless steel absorb more impact energy than what BCC 1018 steels absorb at all temperature whereas the opposite was observed in the experiment for the samples measured at -78 ºC and above. [1] FCC 304 steel samples were expected to show more ductility than BCC 1018 steels samples. These variations can be explained by the large values of standard deviation calculated for the FCC 304 steel measurements, as listed in Table 1. There was some delay in placing the samples, which might affect the temperature and the resulted impact energy measured.

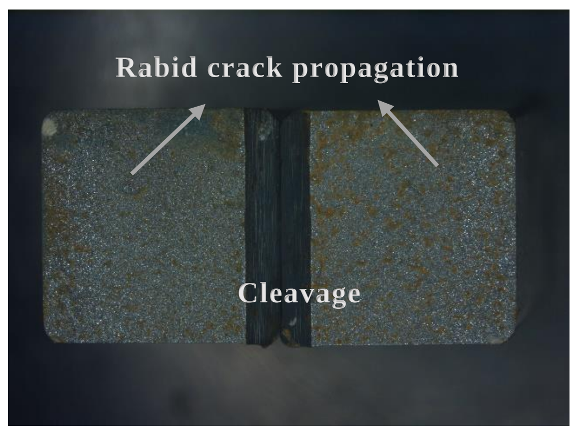
The mode of fracture (ductile or brittle) was determined by observing the overall deformation of the test samples and the fracture surfaces. The types of general fracture regions were also identified on the optical micrographs taken at the extreme temperatures for BCC 1018 steel and FCC 304 stainless as shown in Figure 4.





(a) (b)





(c) (d)

Figure 4. Microphotography of the fracture surfaces of (a) FCC 304 stainless steel at 100 ºC, (b) FCC 304 stainless steel at -196 ºC, (c) BCC 1018 steel at 100 ºC and (d) BCC 1018 steel at -196 ºC.

The fracture surfaces of 304 stainless steel at 100 ºC, 304 stainless steel at -196 ºC and 1018 steel at 100 ºC were found to be rough and irregular in appearance with a considerable change in shape around the area of the notch, indicating ductile fractures. [1] However, the fracture surface of BCC 1018 steel at -196 ºC was found to be shiny and flat with no change around the area of the notch, indicating a brittle fracture. [1] Different fracture zones such as the zone of crack initiation, the zone of crack growth, the zone of shear lips and non-shear lips and the zone of final fracture were observed. [2,3] The fracture surface of FCC 304 stainless steel at 100 ºC showed non-shear lips possibly because one atom in FCC is required to move in the dislocation motion while the fracture surface of BCC 1018 steel at 100 ºC showed 45º shear lips because an array of atoms in BCC is required to move in the dislocation motion to plasticly deform.

Conclusion

The objective of this experiment was to use Charpy impact testing to demonstrate how temperature and the crystal structure (FCC versus BCC) of a metal can significantly influence the metal's ability to plastically deform and absorb energy during impact fracture. Using S1-1D SATEC systems impact tester, 1018 Steel and 304 Stainless Steel were examined at – 196 ºC, - 78 ºC, 0 ºC, 24 ºC and 100 ºC.

Overall, the experiment was successful in showing how temperature and the crystal structure (FCC versus BCC) of a metal can significantly influence the metal's ability to plastically deform and absorb energy during impact fracture. The average impact energy measured at 100 ºC was 282.01 ± 3.58 J for BCC 1018 steel and 178.51 ± 15.65 J for FCC 304 steel. Furthermore, the average impact energy measured at -196 ºC was 2.25 ± 3.58 J for BCC 1018 steel and 104.85 ±15.71 J for FCC 304 stainless steel. It was concluded that the decrease of temperature results in a decrease in the metal's ability to plastically deform and absorb energy. It was also found that that FCC stainless steel does not suffer from ductile to brittle transformations due to the insensitivity of dislocation motion to temperature, resulted from the closed packed structure. However, BCC

1018 steel was determined to have a DBTT of about -101 ºC, bellow which it suddenly losses ductility and becomes brittle.

The experiment implies that DBTT is a very critical parameter in engineering designs because it defines the sudden change in the behavior of a material from ductile to brittle. Because DBTT can be changed by changes in microstructure and composition, it is not considered a material constant. The temperature at which the ductile-to-brittle transition occurs increases with increasing the % carbon. [1,2]

References

[1]M. Rigsbee, Impact Testing of Metals, MSE 335 experiment description, 2016.

[2] W.D. Callister Jr., Materials Science and Engineering: An Introduction, Seventh Edition (Wiley, New York, 2007).

[3]S.V. Panin, P. Maruschak, I. Vlasov, and B. Ovechkin, Theoretical and Applied Fracture Mechanics 83, 105 (2016).