Letting Mr. Charpy Die: Evaluating the Usefulness of Charpy Impact Testing on Ductile Iron

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Introduction

The Charpy impact test is a simple test designed to evaluate materials under dynamic loading conditions. ASTM E23-07^{M}, Standard Test Methods for Notched Bar Impact Testing of Metallic Materials, outlines the test method as well as specimen size and geometry. Typically, Charpy bars are 10mm (0.39 in.) square by 55 mm (2.2 in.) long. In many cases, the bars have a notch machined into them along their length. This notch can be either v- or u-shaped. The bars are then held horizontally in the test fixture while a pendulum is released from a standard, specified height. The height to which the pendulum rises after impacting the specimen allows the tester to determine how much energy was absorbed by the material during fracture. High absorbed energies typically, but not always, indicate ductile fracture and low values typically indicate brittle fracture.

History of the Charpy Impact Test

In the 19th century, the railroad industry, both domestic and abroad, was growing rapidly. With this rapid expansion came a rise in the number of failures in the rails and axles of the rail cars. All of these failures occurred unexpectedly. Scientists at the time did not have a broad understanding of the intricacies of material properties nor how to properly characterize them. As a result, there was a large driving force to better understand materials, their properties and how to characterize them. One of the tests to be developed during this era was the Charpy impact test.

In 1904, French scientist Consideré noted that as the strain rate increased, so did the temperature at which brittle fracture occurred. The following year, in 1905, Georges Charpy developed his impact test based upon an idea by S.B. Russell. The purpose of impact testing is to evaluate the behavior of materials under dynamic loading conditions. At the time Charpy was developing his test, other tests were also in use. Some of these, such as the Izod impact test, later had standards written for them; however, many others fell out of use. BY 1933, the American Society for Testing and Materials (ASTM) had developed a standard, E23[1], to be used for Charpy impact testing.

The full benefit of the Charpy impact test was not realized until World War II. During the war, the United States manufactured upwards of 3000 Liberty ships. Of these 3000 ships, 1200 failed in some way or another. Over two hundred of the failures were considered hazardous while approximately 20 ships broke completely in two. A number of these failures occurred even while a ship was docked. There were three things in common between all these failures: they were sudden, brittle in nature, and occurred at stresses well below the yield stress of the material. In response to the ships' failures, the US government conducted an investigation to try to determine the root cause. The study, conducted at the US Naval Research Laboratory, discovered that the Charpy impact test could detect a ductile to brittle transition in the fracture of steel samples that was not predicted by tensile testing, hardness or chemistry. This was a significant finding. In the report issued at the conclusion of the investigation, the scientists recommended that "some criterion of notch sensitivity should be included in the specification requirements for the procurement of steels for use where structural notches, restrain, low temperatures or shock loading might be involved."[2]

Today, the Charpy impact test is used in a number of ways. Test machines are often instrumented to record the energy absorbed during fracture. By testing at varying temperatures, one is then able to construct impact energy vs. temperature curves. For body-centered cubic materials (such as steel and cast iron), these curves resemble an elongated 'S' as shown in Figure 1. Either the inflection point of the curve or the point at which the fracture is 50% brittle, as determined by examining the fracture surface, are used to determine the ductile-to-brittle transition temperature. This transition temperature is not a material property though, and should not be used for design purposes; material properties such as fracture toughness, K_{Ic}, should be used instead. Despite this, there are still a number of instances when a specification includes a minimum Charpy impact energy requirement. Nuclear pressure vessels and steel bridge designs both have this requirement[3]. A number ductile iron standards, including ISO 1083:2004[4] (Spheroidal graphite cast irons), DIN 1563[5] (Founding – Spheroidal graphite cast iron), ASTM A571[6] (Austenitic Ductile Iron Castings for Pressure-Containing Parts Suitable for Low-Temperature Service) and ASTM A897[7] (standard specification for Austempered Ductile Iron Castings) all require minimum Charpy values as well. DIN 1563 has different minimum impact values based upon the section size of the casting; in general, the impact requirement decreases as section size increases.

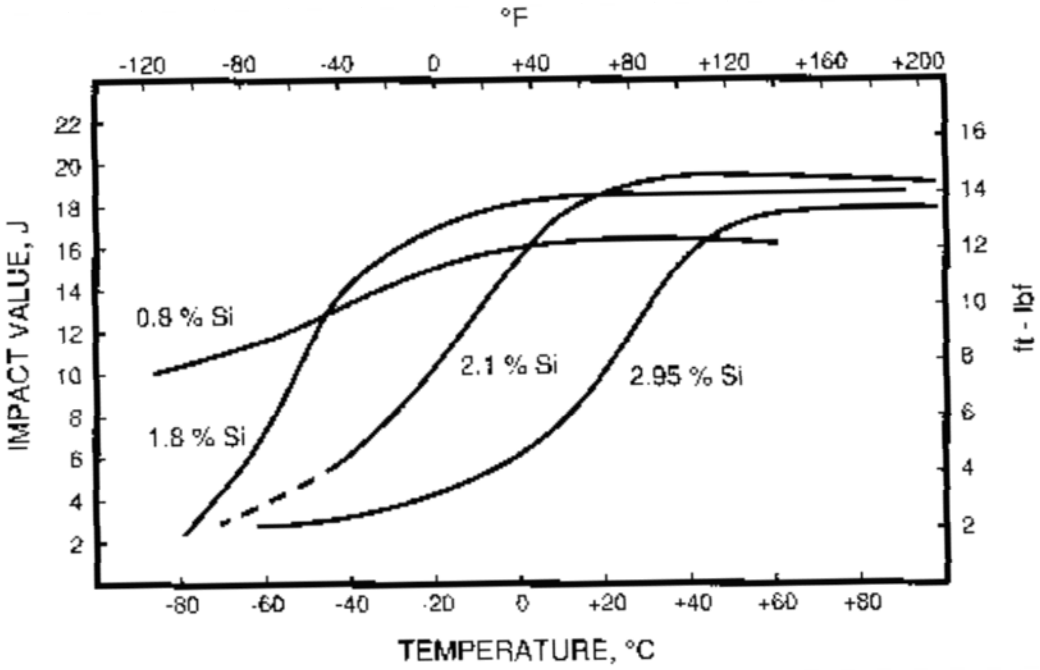


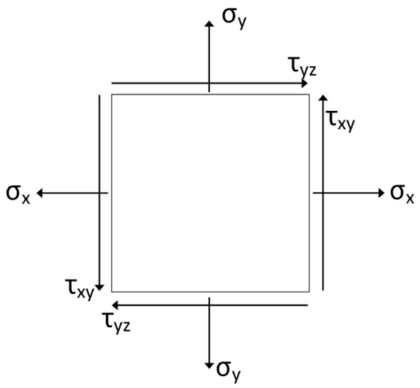
Figure 1: Impact energy vs. temperature curves for ductile iron. Image courtesy of the Ductile Iron Society Ductile Iron Data Handbook.

The Charpy Test Explained

Inherent in the Charpy impact test are high strain rates. These are so high, in fact, that in practice, they are representative only of ballistics-type applications. While the high strain rates have their place, they are not characteristic of the majority of impact loading instances. Furthermore, due to the small size of the Charpy specimens, a complex stress state develops which is not indicative of real world applications. In real components, the plain strain condition (explained later) is often the dominate state. It is possible to impose this on Charpy specimens, though, using proper sample preparation methods.

Shear Stress vs. Shear Strain

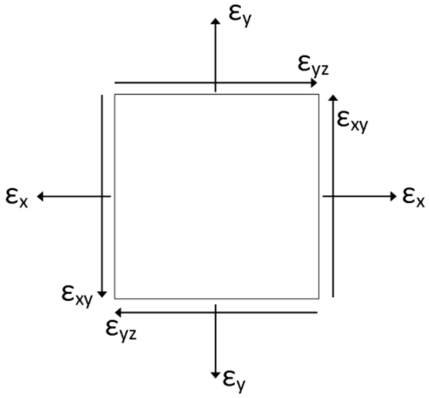
Plane stress is the stress state in which one of the principal stresses is zero. This is shown graphically in Figure 2. The plane stress state typically develops in components when one dimension is much smaller than the other two (i.e. a plate).



$$\sigma_z = \tau_{xz} = \tau_{yz} = 0$$

Figure 2: Graphical representation of plane stress. The equation to the right indicates which stresses are zero.

In contrast, plane strain occurs when the principal strain in the longest direction is constrained and is assumed to be zero. This state is shown graphically in _ and generally occurs in components that have one dimension much longer than the other two (i.e. a prism).



$$\varepsilon_z = \varepsilon_{xz} = \varepsilon_{yz} = 0$$

Figure 3: Graphical representation of plane strain. The equation on the right shows which strains are zero.

Fracture Mechanics of Steel and Ductile Iron

Without going into too much detail, the important points of the fracture mechanics of steel and ductile iron will be described.

Fractured steel Charpy specimens exhibit what are known as shear lips. According to Lai, shear lips form at the boundary between the elastic zone and plastic zone that develop ahead of a crack tip. A number of sources[9,10,11] in the literature state that the presence of these shear lips indicate plane stress behavior within the material. Furthermore, it was shown[10] that steel is much more sensitive to notch geometry than ductile iron, especially with regards to transition temperature and upper shelf energy.

In ductile iron, graphite de-bonding dominates fracture. According to a literature survey conducted by Bradley and Srinivasan[12], Charpy v-notch results are only acceptable "when internodular spacing is less than the standard notch root radius of 0.25 mm. This requires a nodule count of less than $20/mm^2$." This means that a crack must have sufficient matrix material to travel through before it encounters a nodule and this occurs only when nodule counts are 20 or lower. Additionally, In contrast to steel, which experiences plane stress, ductile iron experiences plane strain in a Charpy test[13].

Notch Geometries

There are a number of notch geometries specified in ASTM E23. These include unnotched, v-notched, u-notched, fatigue pre-cracked v-notch and side grooved. Unnotched is typically used for cast irons while v-notched is typically used for steels. U-notched specimens are not common, along with fatigue pre-cracked and side-grooved. However, samples that are v-notched and fatigue pre-cracked tend to have better agreement with results obtained from dynamic tear testing. A sharper notch yields a more conservative estimation of impact toughness and transition temperature. In reality, most cracks that develop in service are sharp and resemble fatigue cracks; therefore, fatigue pre-cracked samples are useful for comparison to results in service components. Side grooving is not, technically, a notch geometry. Rather, it involves machining grooves on the sides of the Charpy bar to, essentially, reduce the cross sectional area at the notch. By doing this, plane strain can be imparted on steel specimens.

Impact Properties of Ductile Iron vs. Steel

Two papers of interest from the literature are reviewed here. Both of them compare the impact properties of ductile iron with those of steel. The first was written by K. E. McKinney at Texas A&M University in 1984 and co-authored by W.L. Bradley and P.C. Gerhardt. The second was authored by R.A. Martinez at the National University of Mar del Plata in 1998. Co-authors included R.E. Boeri and J.A. Sikora.

McKinney, Bradley and Gerhardt[10]

In this study, the authors investigated the impact fracture toughness of ductile iron and compared it to that of cast steel. The two materials were chosen based upon yield strengths. The cast steel was ASTM A216-82 with a yield strength of 36 ksi (248 MPa). The ductile iron chosen was 60-40-18 with a modified

Si content. By lowering the Si content, the authors were able to reduce the yield strength to match the 36 ksi of the cast steel. Four different test bar configurations were evaluated: v-notched, v-notched with fatigue pre-cracks, v-notched with side grooves and v-notched with both fatigue pre-cracks and side grooves. Testing these in an instrumented Charpy tester and at various temperatures, the authors were able to record load-displacement curves for each bar. Using this data, they then calculated the dynamic fracture toughness (K_{Id}) using the following equations:

$$K_{Id} = \sqrt{JE} \qquad J = \frac{2A}{Bb}$$

In the above equations, E is Young's modulus, A is the area under the load-displacement curve, up to max load, B is the specimen thickness and b is the un-cracked ligament.

The authors plotted K_{Id} vs. temperature. From these plots, they were able to determine that side grooving and pre-cracking affected the upper shelf energy more than transition temperature, especially for the steel samples. In general, the cast steel samples had a higher upper energy as well as a higher lower shelf energy compared to the ductile iron. However, the difference in the transition temperatures of the two materials was significant. In the fatigue pre-cracked and side grooved (to constrain to plane strain) steel samples, the transition temperature was approximately 100°F. In contrast, fatigue pre-cracked ductile iron samples had a transition temperature of approximately -40°F. Figure 4 is a plot from the McKinney paper. It shows that in the temperature range of -50°F to 90°F, the ductile iron actually has higher absorbed impact energies than the cast steel.

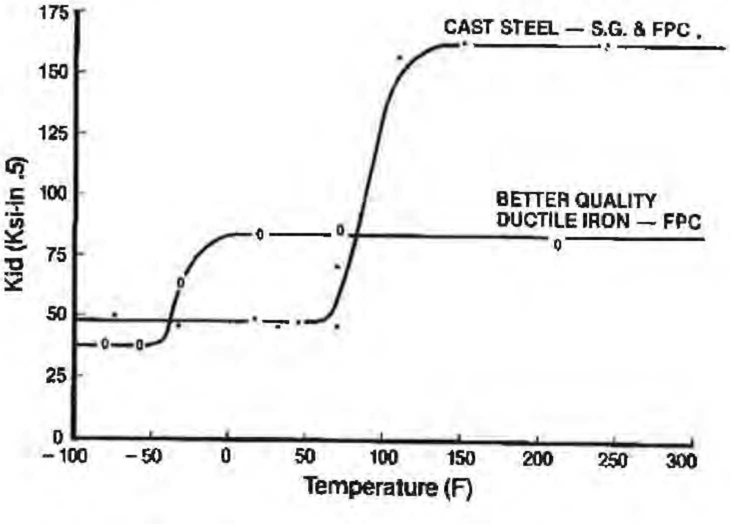


Figure 4: Dynamic fracture toughness vs. temperature plot from McKinney paper.

In this paper, the authors also discussed the comparison of Charpy impact values between cast steel and ductile iron. They state that "it is an apples to oranges type of comparison which may be very misleading if both materials are used in sufficiently thick sections in service to give plane strain conditions."

Martinez, Boeri and Sikora[9]

The authors of this study investigated the difference in impact and fracture properties of two grades of austempered ductile iron with quench and tempered 4140 steel. Similar to the McKinney study, the materials were matched based upon their ultimate tensile strengths (as opposed to yield strength in the McKinney paper). ADI grades 1050-750-07 and 1600-1300-01 were compared to 4140 quenched and tempered steel at two different temperatures. Notched and unnotched Charpy samples were tested as well as fatigue pre-cracked fracture samples.

Two heats were cast to produce the ADI and were labeled as C1 and C2. Heat C1 was of better metallurgical quality than C2 and had a nodularity of 100% and a nodule count of 250. Heat C2 had a nodularity of 80% and a nodule count of 137.

Comparing the data for the notched specimens, one finds that there is not a large variation for the higher strength samples as compared to the lower strength samples. However, when the data from the fracture toughness testing is evaluated, there is even a smaller difference between the steel and ductile iron. In the experimental set up, the authors did not adjust for the difference in fracture modes between the two samples (plane stress for steel vs. plane strain for ADI), but they did comment on it in the paper. According to the authors,

> "The formation of shear lips is the main cause of the significant difference between the Charpy behavior of ductile iron and cast steel…Under plane strain conditions, which could be expected in many component failures, the "shear lip advantage" of steel would be absent, with dramatically lower fracture toughness."

Limitations of the Charpy Impact Test

There are a number of limitations inherent in the Charpy impact test. Some of these are presented here.

According to the appendix of ASTM E23, the transition temperature varies with the size of the bar that is tested, even for the same material being tested. Furthermore, it stated that correlations cannot be made between these different sized bars. Drop weight and drop weight tear testing partially alleviate this issue. Drop weight tests also show better correlation, especially for the transition temperature, between test specimens and in-service parts.

The data generated from a Charpy test – mainly transition temperature – is not a material property. As a result, these values should not be used in design. A number of references state that actual material properties, such as K_{Ic}, should be used, for designing of new components.

The test bars in a Charpy test are small. While this is economically favorable, it does not provide conditions that are representative of a majority of service applications. The stress state produced in these small bars is often far more complex than what an in-service component would experience. Fracture mechanics specimens, while larger, help to reduce this disparity between lab and reality generated results.

As noted in a DIS Hot Topic by James Mullins[14] as well as the ASM handbook[11], a high nodule count in ductile iron runs the risk of reducing the impact toughness of a material. As previously stated, the crack needs enough matrix to travel through and high nodule counts decrease the amount of matrix between nodules.

Finally, Charpy tests measure the TOTAL energy of fracture – both the initiation and propagation energies. According to Annex C of ISO 1083:2004, ferritic ductile irons have similar crack initiation energies compared to low alloyed or unalloyed steels, even when the impact energies of the ductile iron are less than half that of the steel.

Conclusions

Charpy impact testing is neither an accurate nor acceptable way to measure impact toughness in cast irons. It is inappropriate to use it as a means of comparison between cast iron and steel. Although the two materials are comprised of the same two base elements, iron and carbon, they differ dramatically in their material properties. Further research into better means to measure impact toughness of ductile iron is needed. Additionally, design engineers need to be better educated as to what the results of the Charpy impact test actually measure and how to best utilize those results.

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