THE DUCTILE TO BRITTLE TRANSITION

Introduction

Body centered cubic metals lose most of the fracture resistance and ductility when temperature is lowered to below the ductile to brittle transition temperature. This temperature is often the lowest temperature at which a structural engineering material can be considered useful. The transition temperature is also very sensitive to alloy composition and processing. This makes it a useful criteria for quality control. The purpose of this experiment is to measure the ductile to brittle transition temperatures of several plain carbon steels. An aluminum alloy is also tested and compared to the behavior of the steels. The energy of fracture is measured using the Charpy V-notch impact test and the percent ductile/brittle fracture are used to determine the ductile to brittle transition temperature.

Figure 1 A typical Charpy sample, this one showing a mixture of ductile (dull, gray) and brittle (shiny, salt and pepper) fracture modes.

Background

History: Why would a steel that is normally capable of sustaining great loads and capable of ductilities greater than 20 percent suddenly, when cold, become so brittle that it could be shattered by a minor blow or similar impact? This was the question asked over a hundred years ago when fractures occurred in steel structures in severe weather. Since then many similar failures have been documented. There a number of possible reasons for such failures: fatigue, corrosion, fabrication and design errors, poor quality steel, etc. The most dramatic and unexpected cause of brittle failure in ferrous alloys is their tendency to loose almost all of their toughness when the temperature drops below their ductile to brittle transition temperature. This has been the cause for numerous dramatic and catastrophic failures, i.e. the rupture of a 2.3 million gallon molasses storage tank in the winter of 1911, bridge failures, liberty ships breaking in half in the harbor and at sea during World War II and other disasters (see ASTM STP 158, and the figures and text following the references). The earliest record of such failures dates back to 1879. This was when good, cheap Bessemer and open hearth steels had just begun to become widely used. (The Bessemer process was introduced in 1860. Prior to that, steel had been made by an expensive process of carburizing wrought iron. The expense limited the uses of steel to special applications.) The problem of brittle failure of steel structures was severe during and just after World War II. Between 1942 and 1952 around 250 large welded steel ships were lost due to catastrophic brittle failure. Another 1200 welded ships suffered relatively minor damage (cracks less than 10 feet long) while over 1900 riveted ship have broken in two or lost at sea. Over 58 cases of non-ship failures had been reported. Many of these may have failed by non-brittle processes while many failures probably have gone unreported due to adverse publicity it would generate [3].

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The problem of brittle failure has not gone away. It is still encountered occasionally. However, we are now more aware the metallurgical factors that influence the ductile to brittle transition temperature and the design practices and fabrication techniques that could lead to brittle failure.

Ductile to Brittle Transition: The ductile to brittle transition is characterized by a sudden and dramatic drop in the energy absorbed by a metal subjected to impact loading. This transition is practically unknown in fcc metals but is well known in bcc metals. As temperature decreases, a metal's ability to absorb energy of impact decreases. Thus its ductility decreases. At some temperature the ductility may suddenly decrease to almost zero. This transition is often more abrupt than the transition determined by the energy absorbed. This temperature is called the nil-ductility transition temperature (NDTT). The NDTT is lower than the fracture energy transition temperature and is generally more narrowly defined. The differences between these two transition temperatures is related to the high rate of loading during impact testing rate sensitive metals. Increased loading rates cause the yield stress to increase while increasing temperature causes ductility to increase.

The fracture energy transition temperature range might not be narrow enough to be able to identify a unique transition temperature. This is often the case for steels. The width of this range varies for different alloys. Fracture in this range is a mixture of ductile and brittle modes of failure. Often criteria other than the energy transition are used to define the transition temperature. One method is to specify a fracture energy below which the material is considered to be brittle. Sometimes the temperature at the halfway point in the transition is regarded as the transition temperature. Another method is to define the ductile to brittle transition in terms of a specified amount of ductile and brittle fracture. For this method the proportion of ductile-brittle fracture is estimated by examining the fracture surface. A 50% ductile-brittle fracture surface is the criteria often used to define the ductile to brittle transition temperature. Figure 1 illustrates several methods for measuring the transition temperature.

An examination of a fracture surface will reveal whether fracture occurred by ductile or brittle processes. To the unaided eye a brittle fracture surface has a grainy, salt and pepper appearance. Examination with an SEM clearly reveals the cleavage appearance, river lines and planar microcracks characteristic of brittle fracture. Brittle fracture can occur intergranularly or transgranularly. Ductile fracture can be recognized by its dull appearance. Ductile fracture is usually transgranular and its fracture surfaces show a significant amount of plastic deformation between roughly spherical microvoids.

Charpy V-Notch Impact Testing: The Charpy test is a three point bend impact test. It requires a specimen containing a machined notch in the center of the face facing away from the impacting device and a sturdy machine that can impart a sudden load to the specimen. The Charpy tester consists of a heavy pendulum which is allowed to strike the specimen at the bottom of its arch (maximum kinetic energy, maximum velocity). As the specimen deforms and fractures a portion of the kinetic energy of the pendulum is transferred to the specimen. The specimen is broken and the two pieces of the fractured specimen are knocked clear of the testing machine while the pendulum continues its swing to a somewhat lower position than it was released from. The differences in these heights and the mass of the pendulum determines how much energy was absorbed by the specimen. Most impact testers have a gage that reports this energy so that it doesn't have to be computed.

Originally, the Charpy impact test was a crude shop test that was developed to evaluate the effect of notches on fracture behavior. In 1926 ASTM proposed a method for impact testing. In 1933 ASTM standard E-23 was tentatively issued and has subsequently been revised several times. The US Army became involved in 1935. They had discovered that there was an excellent correlation between the ballistic performance of armor and fracture toughness as measured by the Charpy test. However, they found that there was a wide variation in results of impact tests even from qualified laboratories. Upon visiting different installations they found horrible conditions, worn, unsecured and miss-aligned machines, improper centering of the specimen and generally poor procedure. The Army was interested in assuring the accuracy of the results of Charpy tests. They (and others) investigated the effect of variables in testing machines, specimen geometries and test procedures. They also set out to find a method for mass producing specimens that could be used as standards. In 1955 the Army initiated a program of certifying machines on Army contracts. In the early 1960's they began offering the program to the private sector. This program is still offered. For a small charge, the Army will supply standard specimens. After testing them, the specimens could be sent back for further evaluation of the testing machine and, if it passes, the testing machine will be certified. In the first years of the program the rejection rate was 44 percent. A few years later it had dropped to 14 percent. [6] The program is still offered.

Standardization of the Charpy test helped the Army argue for increased alloy contents of steels and for more severe quenching practices when producing steel used as armor. It has also resulted in metallurgical innovations that have led to the development of metals with significantly higher impact resistances at similar strengths and hardness. Standardization has also allowed a large data base to be compiled which has enabled correlations to be made with service performance.

Current applications of the Charpy impact test include comparisons of heat to heat variations of steel, evaluation of material behavior during either intentional or accidental high rates of loading, evaluation of the effect of irradiation on the embrittlement of steel, evaluation of the effects of microstructure and fabrication on toughness and studies of the fundamental aspects of deformation in bcc materials. Together the tensile test and Charpy impact test form a fairly complete evaluation of the mechanical properties of a material. However, it should be noted that the Charpy test is not a simulation of an alloy in service. The results of the Charpy tests are useful indications of how the material might behave in service.

The Charpy impact test is a relatively simple, quick and inexpensive method for testing the dynamic fracture behavior of materials. It has been used extensively, particularly on ferrous alloys and has been standardized in ASTM E23 [1]. However, there are many criticisms of the Charpy test. The principle one is its lack of a meaningful correlation with another fracture mechanics property, K_{Ic}. Also, even when carefully and properly performed, inaccurate data can be reported. However, the Charpy test is still considered to be the best fracture mechanics test in terms of the information gained per dollar spent.

ASTM E23 describes the Charpy test in detail. Much of the utility of the Charpy test comes from the large amount of data and correlations with service that are available. The utility of new data depends on how closely one follows the standard procedure, the geometry of the specimen, and the calibration of the machine. A number of lesser details can have a significant effect on the results. Several of these, plus some additional guidelines are listed below. This list should also provide some insight into the character of the Charpy impact test.

- The specimen cannot absorb more than 80% of the maximum energy capacity of the pendulum.

- The testing machine must be level and bolted securely to the floor.
- Alignment of the striker and the center of the specimen should be checked frequently.
- Slop in the axle and bearings should be within specified limits.
- The testing machine should be calibrated periodically. Windage and friction should be checked frequently.
- Specimen geometry, size, square and especially the acuity of the notch is critical. Variations of 0.005 inches in the depth of a V-notch can alter the results by 10 joules, almost 10 percent of the impact resistance of a tough material.

When conducting a test keep the following things in mind:

- The trigger mechanism should permit smooth release of the pendulum.
- The broken parts of the specimen must not interfere with the movement of the pendulum.
- No more than five seconds can elapse between the time the specimen is removed from the heating or cooling media until it is correctly seated in the specimen holder and tested.

One on the major drawbacks of the Charpy test is that it doesn't provide much information about the fracture process itself. Therefore, instrumented Charpy tests have been developed. A strain gage is mounted on the arm of the pendulum and a fast, triggered data acquisition system records the impact. The data provides load-time profiles that show the different stages of deformation and fracture: general yield, maximum load, fast fracture and arrest load after fast fracture. In addition, the actual energy absorbed can be obtained by accounting for the decrease in velocity of the pendulum as it fractures the specimen. The ability to separate the total energy absorbed into its different components makes the instrumented Charpy test an effective analytical tool. It was developed so that fracture behavior could be predicted from metallurgical fracture parameters. This goal has not yet been achieved.

There are several variations on the basic Charpy impact test. The most common type of Charpy test uses a V-notched specimen. Three others are the Charpy keyhole test, Charpy U-notch test and the precracked Charpy test. The Charpy keyhole and U-notch tests are similar to the Charpy V-notch test. Only the geometry of the machined notch is different. These tests generally yield higher values of toughness and lower transition temperatures. These tests are more appropriate when testing materials that are less ductile or have a high notch sensitivity. Cast irons show practically no sensitivity to the presence of a machined notch. Apparently the internal graphite flakes have the same effect as the external notch. Cast irons are often tested using un-notched specimens.

In the pre-cracked Charpy test, a small fatigue induced crack is produced in the root of the notch. The specimen is then tested in the normal manner. The pre-cracked Charpy test has two principle advantages, it is not complicated by details and accuracy of the machined notch and the sharp crack is similar to those encountered in service and those used in K_{Ic} fracture toughness tests. Several correlations have been made between K_{Ic} (static) and Charpy tests. None are particularly useful due to scatter in the data. Better results have been obtained with K_{Id} (dynamic) tests, figure 2. The main problem in these correlations is the differences in loading rates, especially for rate sensitive materials. However, the pre-cracked Charpy can be used to determine the ductile to brittle transition temperature.

The Izod test is similar to the Charpy V-notch test. In fact the same testing machine can be used. Only the specimen geometry and computation of the impact toughness is different. The Izod test is a cantilever-bend test. The specimen has a V-notch which is located toward one end of the specimen instead of in the middle as in the Charpy V-notch specimen. The use of the Izod test is preferred in Great Britain (BS131). The Charpy test is preferred in the United States. It is also standardized under ASTM E23.

Preparation

1. How can simple static tension tests be used to measure toughness? Notch sensitivity?

2. Briefly, describe the Charpy and K_{Ic} tests and note their differences. What are the important variables in each?

3. Compile data on the mechanical properties of the alloys that will be tested in this experiment. (Hardness, yield point, UTS, elongation, reduction in area, Charpy toughness and transition temperature, K_{Ic}, etc.)

4. Given an impact tester whose head has a mass of 27.25 kg and a drop of 1.34 m, compute the kinetic energy and velocity of the head just prior to impact. Friction and windage are negligible.

5. Why do bcc metals undergo a ductile-to-brittle transition while fcc metals do not? What is the reputation of hcp metals in regards to toughness?

Materials

Standard Charpy V-notch specimens made from the following alloys:

Alloy	Condition
1018 Steel	Cold Finished
1045 Steel	Cold Finished
1095 Steel	Hot Rolled
304 Stainless Steel	
6061 Aluminum	T-651

Equipment

Heating and cooling baths (in safe containers with covers) that provide specified specimen temperatures.

Furnace	200°C
Boiling water	100°C
Room temperature	25°C
Ice Point	0°C

CO_2 (sublimation)	-78.5°C
Liquid Nitrogen	-194°C

For temperature measurement use a thermometer or thermocouple (type E or K). Also needed are tongs, gloves, goggles, etc. to safely handle the specimens. Impact testing will be conducted using the Tinius-Olson Charpy/Izod impact tester. A Rockwell hardness tester will also be used in this experiment.

Procedure

Use an engraver to mark identifying numbers on each specimen. Keep the numbering system simple. Mark both halves but do not mark the specimens in an area that might affect the results.

Measure the hardness of each specimen. This simple test will be used to provide an additional basis for comparison to published data.

Place one specimen of each alloy in each of the heating/cooling baths. Let them soak for at least twenty minutes before testing. Monitor the temperatures of each bath to make sure they are stable and at the specified temperatures before testing any specimens.

Impact test one specimen of each alloy and temperature. Check the temperature of the heating/cooling medium just before selecting a specimen. Don't waste any time between removing the specimen from the heating/cooling medium and loading and testing it (less than 5 seconds). However, don't be too hasty and compromise laboratory safety. If you miss the 5 second window, the specimen can always be reheated/recooled.

Record the impact energy and examine the fracture surfaces. Estimate the relative areas of brittle and ductile fracture. Store the specimens in a safe place for future reference.

Examine the fracture surfaces using a low power optical microscope. Note characteristics of ductile and brittle fracture. Prepare one or two specimens for SEM fractography. (Optional)

Analysis

1. Compare the hardness readings to those of similar materials and heat treatment.

2. Plot total energy absorbed and percent ductile fracture against temperature. Identify the transition ranges and temperatures.

3. Comment on the appearance of the fracture surfaces, especially any details seen through the microscope. Note trends in fracture behavior with temperature and alloy composition.

4. Compare Charpy impact toughness with toughness estimated from the true stress-engineering strain curves of similar alloys.

References

1. Standard Methods for Notched Bar Impact Testing of Metallic Materials, E 23, Annual Book of ASTM Standards, v. 03.01, ASTM, Philadelphia, 1984, pp. 210-233.

2. Mechanical Testing, Metals Handbook, Ninth Edition, vol. 8, ASM, Metals Park, Ohio, 1985,

pp. 259-297.

3. Shank, M. E., in Symposium on Metallic Materials at Low Temperatures, ASTM STP 158, 1953, pp. 45-110.

4. Pellini, W. S. in Symposium on Metallic Materials at Low Temperatures, ASTM STP 158, 1954, pp. 216-258.

5. Sailors, R. H. and Corten, H. T. in Fracture Toughness, ASTM STP 514, 1971, pp. 164-181.]

6. What does the Charpy test really tell us?, ed. Rosenfield et al., ASM, Metals Park, Ohio, 1978.

{Photos: Failures of ships and stationary structures due to the embrittlement of steel. From articles in ASTM STP 158. Not available at this time.}

Figure 1. Three methods of measuring the transition temperature [4].

Figure 2. Correlation between fatigue pre-cracked Charpy specimens and fracture toughness, K_{id} [5].