Advances In Notched Bar Impact Testing

A 100-Year-Old Test Gets a Face Lift

by Michael P. Manahan Sr.

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The Early Days of Impact Testing

The earliest known publication on the effects of impact loading on materials was reported in the early 1800s by Tredgold[1] and was a theoretical discussion on the ability of cast iron to resist impulsive forces. In 1849, the British formed a commission to study the use of iron in the railroad industry. This commission began its work by considering practical approaches to impact testing.[2] In 1857, Captain Rodman[2] devised a drop weight machine for characterization of gun steels and over the next 30 years, this machine was widely used in the testing of railroad steels and for qualification of steel products. The drop weight test uses a rectangular bar specimen that rests on two supports; a hammer is vertically dropped to strike the specimen in the middle. The development of the drop weight test in the mid-1800s appears to be a logical extension of the widespread use of pile drivers in construction. From the time of the development of the drop weight machine until the late 1800s, all drop weight tests were conducted using smooth (no notch or crack starter) rectangular bars. While the test worked well for brittle materials, where it is easy to initiate a crack, ductile materials would only bend and it was not possible to induce fracture. LeChatalier introduced the use of notched specimens while conducting drop weight tests in 1892.[3] It was discovered that some steels that showed ductile behavior (bending without fracture) in a smooth rectangular bar, would exhibit fragile behavior when the test specimen was notched.

The first pendulum impact machine was designed by S. B. Russell and coworkers in May, 1896. Actual test results using the pendulum machine were reported in 1897 at an American Society of Civil Engineers (ASCE) conference that was published in the ASCE transactions in 1898.[4] Russell tested both smooth and notched specimens and found that notched specimens were preferred for testing ductile materials because the specimen could be completely fractured when notched. The pendulum impact machine had been conceived by Russell to enable the measurement of the energy absorbed by the specimen during fracture, and this machine was a prototype of the pendulum machine used throughout the world today as specified in ASTM Standard E 23, Standard Test Methods for Notched Bar Impact Testing of Metallic Materials.

In 1901, a French researcher named Charpy published his work[5] (the second publication in the world on pendulum machine testing) on notched bar impact tests. Charpy's tests used a pendulum impact machine based on the design developed by Russell. It is interesting to note that because of Charpy's early involvement with the notched bar pendulum impact test, this test is referred to throughout the world today as the "Charpy" test. However, this test was first conceived of and developed by Russell. In fact, Charpy's 1901 publication[5] reviews the impact test techniques that had been developed for metals qualification and references the paper presented by Russell to the ASCE in 1897. Charpy adopted Russell's test because it has a significant advantage over the drop weight test: the energy absorbed by the specimen can be measured directly. It can be concluded that it may be appropriate to rename the notched bar pendulum impact test, commonly called the Charpy test, the "Russell" test. In this article the test method will be referred to as the "notched bar impact test." The notched bar impact test has been applied to a wide variety of materials, however, this article will only consider application to metals.

Current Practice in Notched Bar Impact Testing

The notched bar impact test requires an essentially rigid test machine that is securely anchored to a massive base (usually constructed using concrete) as shown in Figure 1. A striker, which typically weighs 27 kg, is released from a height (H_1) (approximately 1.5

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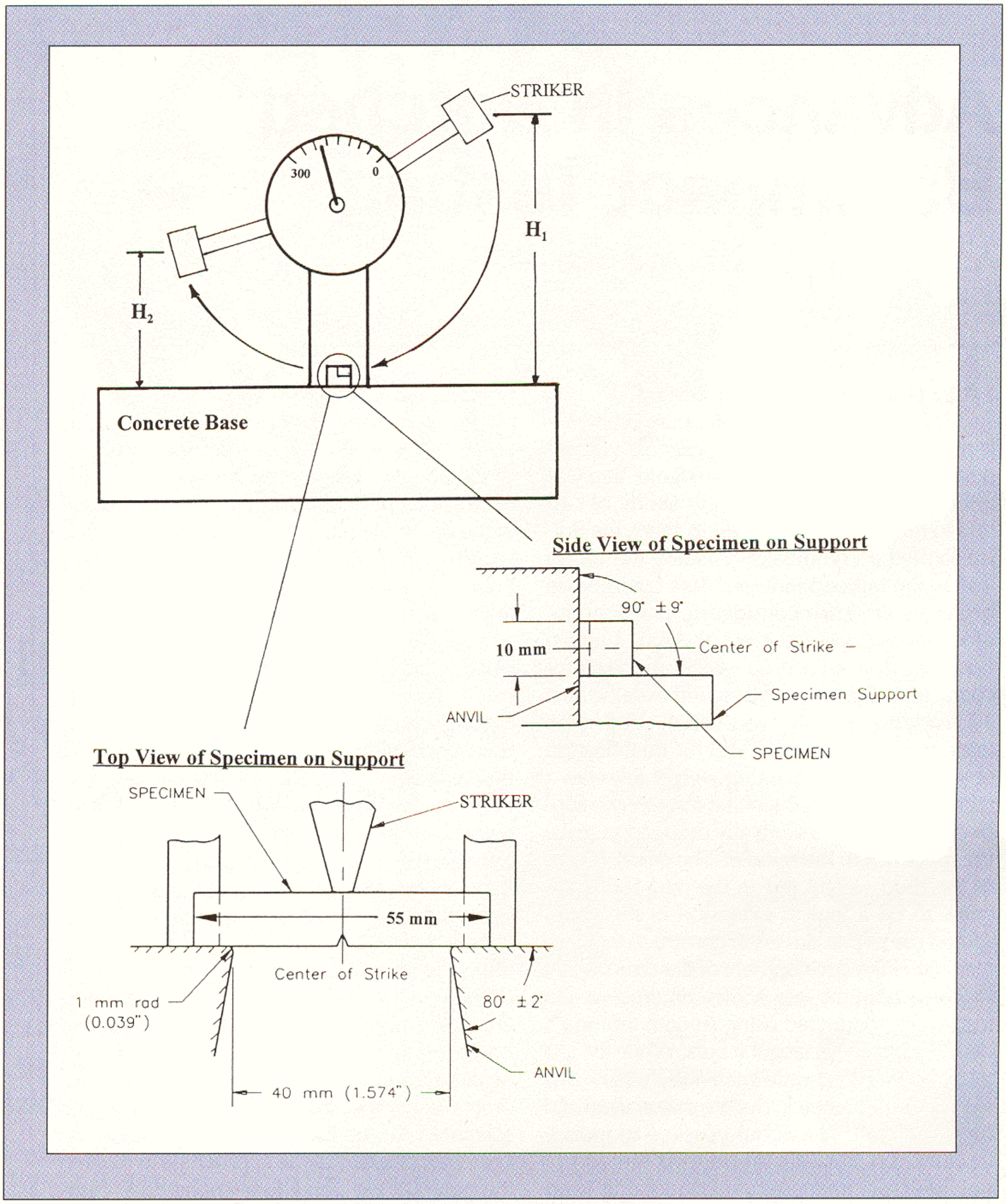
Figure 1: The conventional notched bar impact test measures the energy absorbed in fracturing a V-notched rectangular bar. The data can be correlated with service performance to ensure the selected materials meet their design objectives.



m for a 400 J machine) and allowed to strike the specimen (10 mm x 10 mm x 55 mm), which rests on supports against two anvils. Upon impact, the specimen is in three-point bending (the three points of contact being the striker and the two anvils), which results in the initiation and propagation of a crack from the root (bottom) of the notch. In most cases, complete fracture occurs and the two halves of the specimen are thrown forward as the striker passes between the anvils. After breaking the specimen, the striker rises to a height (H_2). A first approximation of the energy absorbed in breaking the specimen can be calculated as the difference in potential energy before release of the striker (at height H_1) and the potential energy at the instant of zero velocity (at height H_2) after specimen impact. In actual practice, corrections for windage and friction are made to obtain the best measurement of the energy absorbed in breaking the specimen.

Prior to the development and widespread use of modern fracture mechanics over the past 40 years, engineers used notch impact tests to create conditions in a small test piece that would simulate or conservatively bound in-service component failures without having to perform expensive full scale tests. The notched impact test has the important feature that it can suppress the capacity of the material to plastically deform (ie., reduce its apparent ductility). This reduced ductility is partly due to the elevation of the yield stress associated with testing at high strain rates (impact). The multi-axial stress field caused by the notch elevates stresses to levels well beyond the yield stress, thus, also reducing apparent ductility. Testing at low temperatures also tends to limit ductility by increasing yield stress.

When the notched bar impact test is applied to body-centered-cubic (BCC) metals such as ferritic bridge, ship, and nuclear pressure vessel steels, the yield strength is far more sensitive to temperature and strain rate effects than in other materials such as face-centered-cubic metals (aluminum, copper, and stainless steel). In fact, ferritic steels exhibit transitional fracture behavior as shown in Figure 2. Transitional fracture refers to the change in fracture mechanism, typically from brittle to ductile, as the temperature of the test is increased. When the test is performed at relatively low temperatures, the material undergoes cleavage (often referred to as brittle) fracture and the absorbed energy is very low. This region of the "Charpy curve" is often referred to as lower shelf, and crack extension is very rapid and cuts across the grains of the metal. In this low temperature range, the cohesive strength (the atomic bonds that hold the metal together) of the material is exceeded before any significant amount of plastic deformation can occur. As the test temperature is increased, mixed mode fracture occurs and this temperature range is called the transition region. The fracture surface in the transition region shows faceted cleavage (a bright shiny area) in the center with fibrous ductile fracture surrounding the central brittle portion. Finally, when testing is performed at temperatures above the transition region, entirely ductile fracture is observed. Considerable deformation occurs before the final fracture and the fracture surface appears fibrous. The fracture occurs by void initiation, growth, and coalescence and the temperature range over which entirely ductile fracture occurs is called the upper shelf region.

Notched bar impact data do not directly provide engineering data that can be used in structural integrity analyses. Therefore, it is necessary to conservatively correlate the key test parameters with component performance objectives. An important illustration of this approach is the nuclear industry's reactor pressure vessel integrity program. As illustrated in Figure 2, the nuclear industry uses the 41 J index to define a ductile-brittle transition temperatue (DBTT). The effect of neutron irradiation is to shift the transition region to higher temperatures (ΔT_{41}) and the Nuclear Regulatory Commission (NRC) sets screening limits on the maximum shift in the energy-temperature curve that can occur during the life of the plant. If the screening limits are exceeded, then the plant must be shut down or a thermal anneal

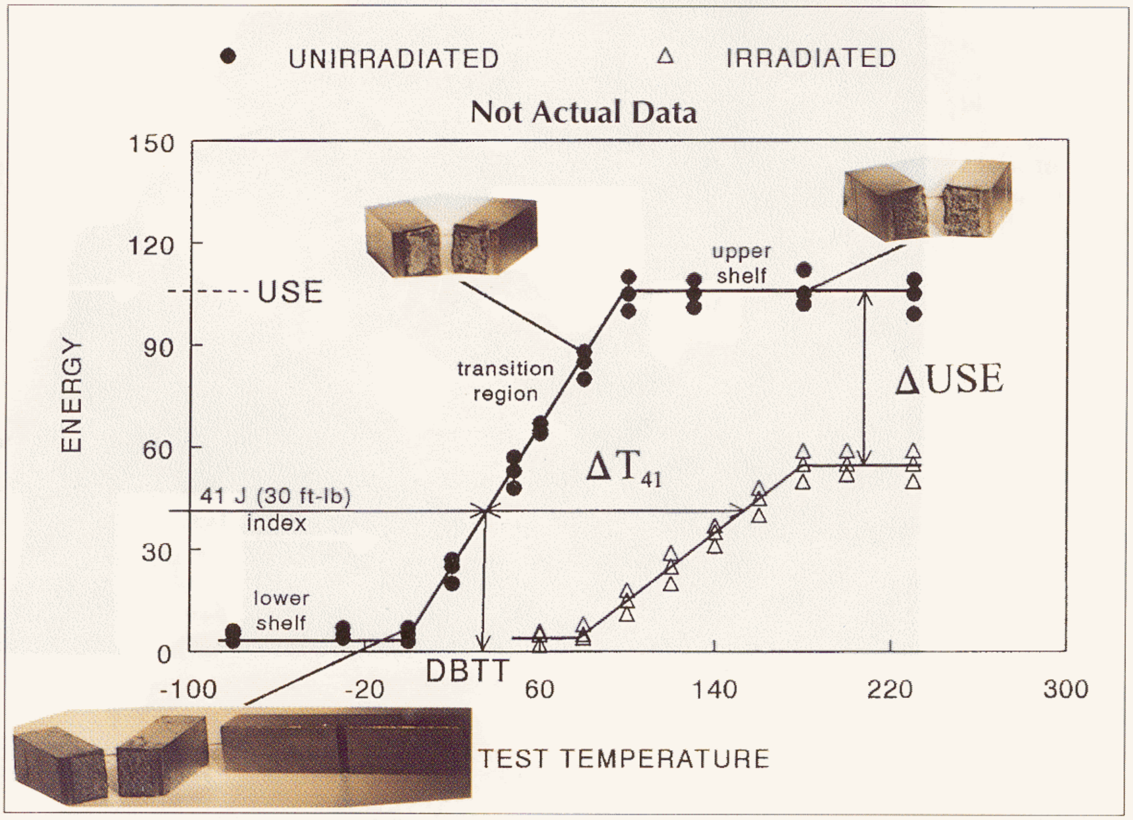


Figure 2: Some materials, such as ferritic pressure vessel steels, exhibit a transition in fracture behavior as the notched bar impact test temperature is increased. At low temperatures the fracture is predominantly cleavage; at intermediate temperatures the fracture is a mixture of both cleavage and ductile; and above the transition region the fracture is entirely ductile.

must be conducted to restore the material properties. The ability of the material to withstand ductile fracture is judged by the upper shelf energy (USE). The NRC requires an in-depth fracture mechanics assessment if the USE is expected to drop below 68 J.

Specimen Miniaturization

In practice, situations often arise where there is not enough material available to fabricate a conventional V-notch (CVN) specimen or where more data is needed from a fixed volume of material. An important application is the surveillance of nuclear reactor pressure vessels (RPVs) where a fixed number of CVN specimens are placed on the inner diameter surface of the RPV at initial startup for monitoring the embrittlement from neutrons. The radiation damage for many plants throughout the world has been more extensive than originally anticipated and these plants will, in all likelihood, require a thermal anneal at some point in their operating history. For other plants, more data are needed to develop plant-specific embrittlement trend models so that overly conservative generic trend models developed by regulators can be avoided.

As illustrated in Figure 3, eight miniature specimens (nominally 5 mm x 5 mm x 25 mm) can be machined from the broken halves of one conventional specimen. This results in an eightfold increase in the number of data points obtainable. In cases where more data are required, the broken halves of the miniature specimens can be welded to produce additional test specimens, resulting in a total of twenty-four miniature specimens starting with the volume of one CVN.

Miniaturization of fracture specimens results in a loss of constraint (i.e., resulting in a two dimensional stress field instead of a three dimensional field) near the notch due

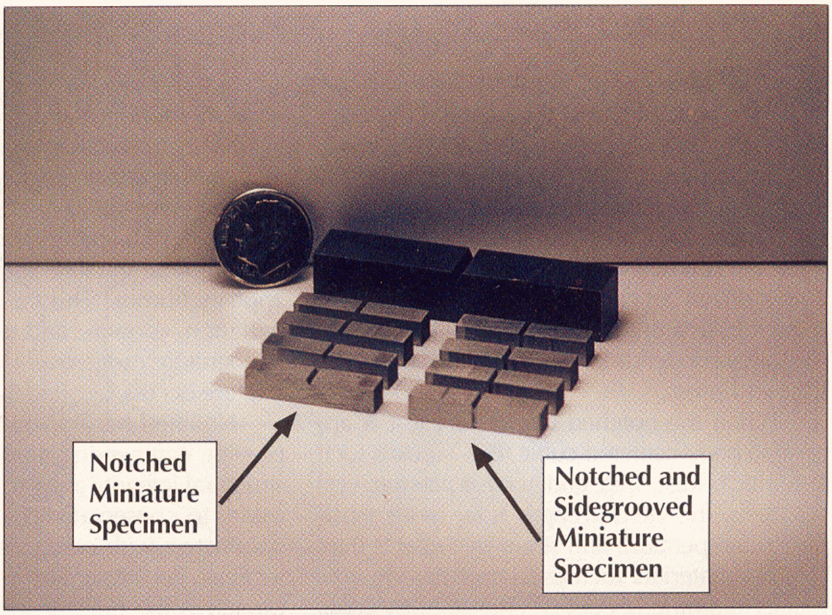
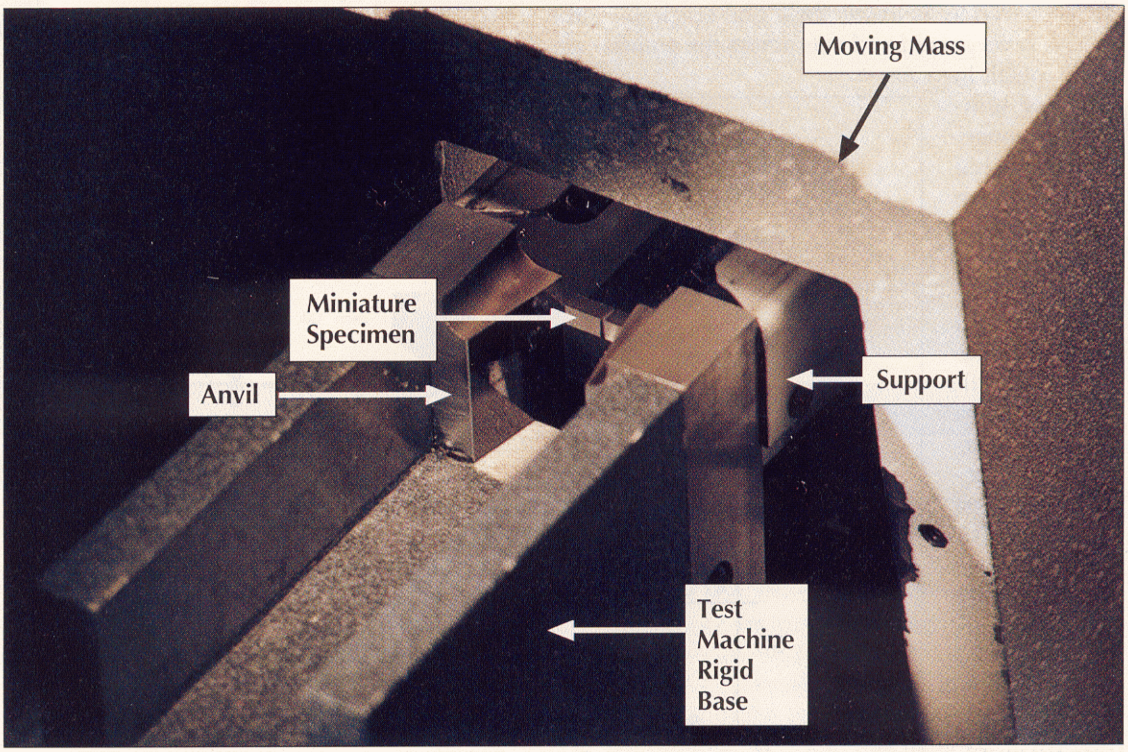


Figure 3: Miniaturization of the notched bar impact test is highly desirable in situations where additional data are needed and only a limited volume of material is available. (Above) Eight miniature specimens can be machined from the broken halves of one conventional specimen. (Below) Conventional test machines can be used with suitable modifications to the supports, anvils, and striking bit.[8]



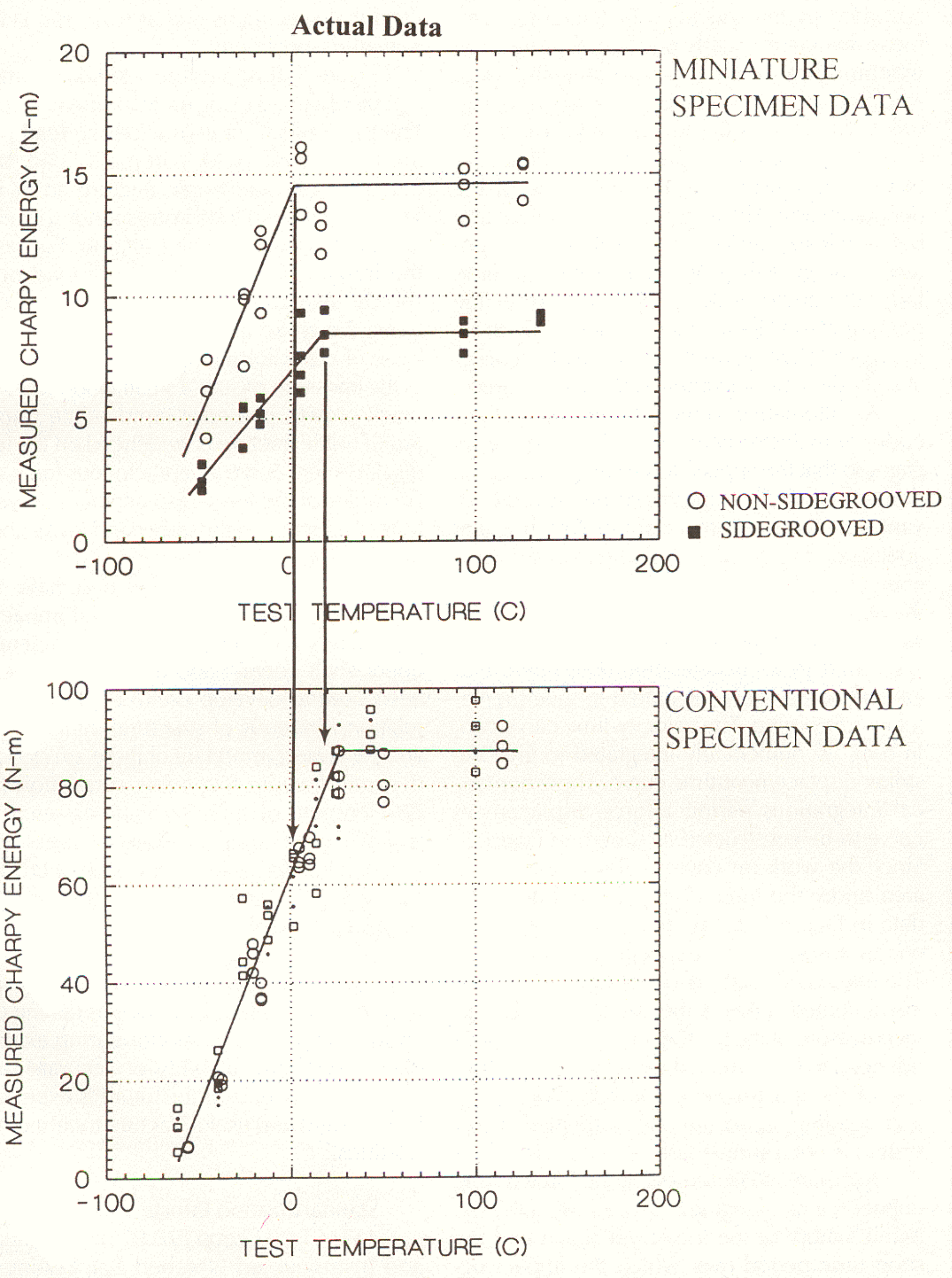


Figure 4: It has been demonstrated both analytically and experimentally that sidegrooving miniature specimens minimizes the loss of constraint associated with miniaturization and produces a stress field that reasonably simulates that of the conventional specimens.[8]

to the well-known size effect of fracture mechanics. This causes a downward shift of the energy temperature curve (see the open-circle minature specimen data in Figure 4). However, a new technology[6] enables miniaturization of this effect by sidegrooving the miniature specimen (see Figure 3). The miniature specimen data are compared with CVN data in Figure 4. The sidegrooved data do not shift downward in temperature and therefore do not require a correction factor to accurately represent CVN behavior. This result is consistent with finite element calculations[7] which demonstrate that sidegrooved miniature (half size) specimens produce a plane strain deformation region along the notch that is about 80% as large as that experienced in a standard CVN specimen.

Striker Instrumentation

As discussed earlier, the basic notched bar impact test involves measurement of the energy absorbed by the specimen in fracturing. This measurement is usually performed using a test machine dial (calibrated pointer and gage mounted on the test machine) as shown in Figure 1. More recently, test machine manufacturers have offered an optional optical encoder that continuously measures the angle of the pendulum arm. The angle of the pendulum arm before release can be used to calculate the potential energy of the system before the test. Similarly, the angle of the pendulum arm at the point of zero velocity after impact (position H_2 in Figure 1) can be used to calculate the energy absorbed by the specimen as described earlier.

An alternative to the dial and optical encoder is to instrument the striker with strain gages so that the applied force can be measured during impact. This approach has several advantages, the most important of which is that additional data (ie., data in addition to absorbed energy) can be obtained. Knowing the mass of the striker and using a special strain gage system, the force-time curve can be measured and converted to an acceleration-time curve that can be numerically integrated to give the velocity-time curve. The velocity-time curve can, in turn, be numerically integrated to give the striker displacement-time curve. These numerical integrations permit a force-displacement curve to be constructed as shown in Figure 5. Since the work (or energy) of a system is the area under the force-displacement curve, the data in Figure 5 can be integrated to give the energy absorbed by the specimen in fracturing. The integrated total energy obtained from the instrumented striker is theoretically a more direct measure of the fracture energy since it does not need to be corrected for windage and friction of the test machine. However, designing and building an accurate instrumented striker system is not a simple task.

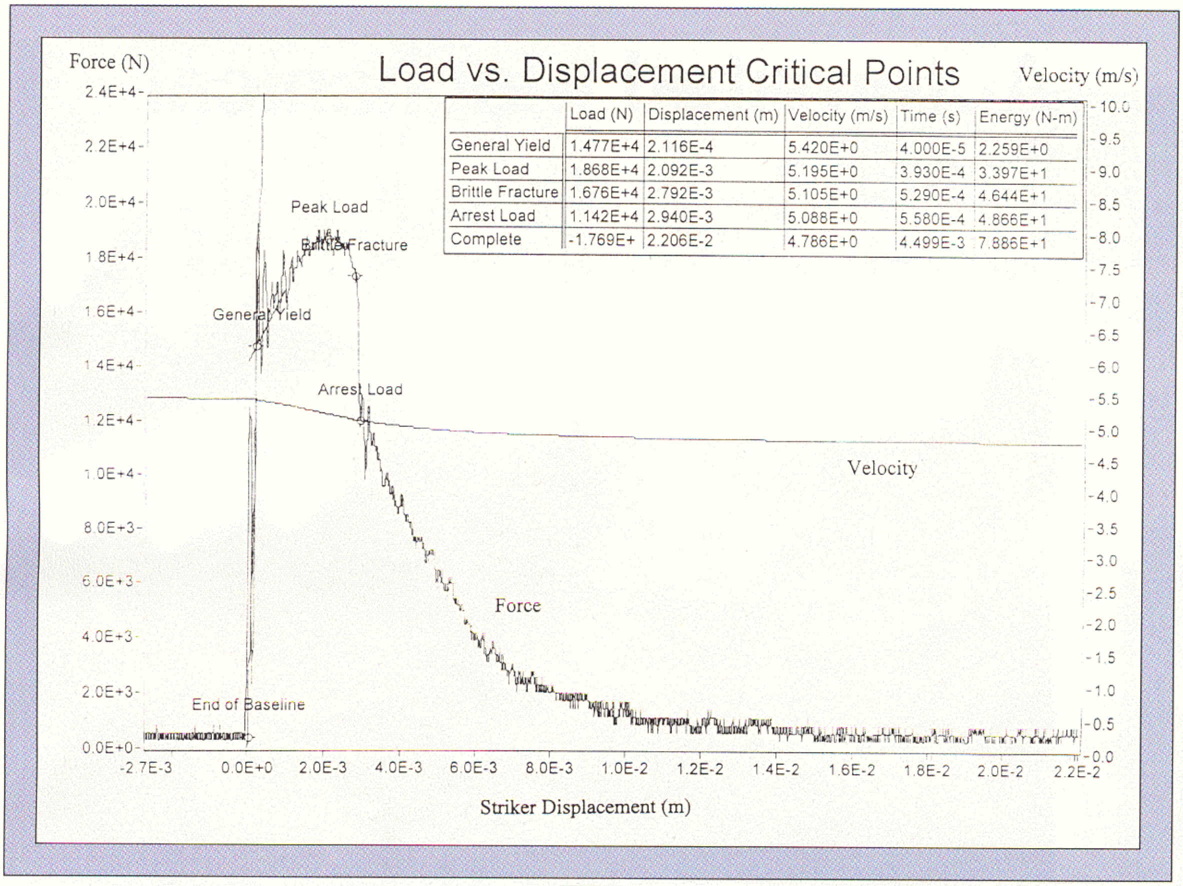
Accurate measurement of the force during impact is a challenging task because of the dynamic nature of the measured signal and the short time period over which the impact occurs (typically one to five milliseconds for steel specimens). The dynamic character of the force signal requires the acquisition of at least 2000 data points to accurately represent the oscillations in the applied force. Because of the data size requirement and short test duration, the storage of the force-time data must be precisely triggered. This can be accomplished by continuously monitoring the load signal and saving data when a significant rise (well above the noise level) in the load occurs. Rapid load change events, such as acceleration of the specimen up to the speed of the striker and brittle crack propagation, require a system response capability of at least 100 kHz for conventional specimens and at least 200 kHz for miniature specimens.

Figure 5 illustrates the additional data that can be obtained using an instrumented striker. The four critical (or characteristic) load points are the general yield load, peak load, brittle fracture load, and brittle fracture arrest load. The general yield load corresponds to yielding across the entire notched section. For tests in the transition region, the peak load occurs shortly after the formation of a sharp crack along the entire notch surface and is an indicator of crack formation in the test specimen. In the transition region, a small amount of stable crack growth precedes rapid brittle fracture. Rapid brittle fracture is evidenced on the force-displacement curve as a precipitous force drop. Examples of the force-displacement curves for tests conducted on the upper and lower shelves are also shown in Figure 5.

Data from instrumented tests have been used to measure the conventional impact test parameters (i.e., 41 J transition temperature, upper shelf energy) and these data have also been used to develop useful engineering correlations. In terms of structural integrity assurance, the most important of these are static and dynamic fracture toughness correlations. The development of such correlations seems reasonable given that the state of stress in the notched bar specimen at the time of crack initiation is plane strain, which is the same state of stress present in relatively thick fracture toughness specimens. Also, several researchers have shown that the bend bar geometry is the best of all geometries in terms of retaining crack tip (or notch) field constraint during extensive plasticity. The availability of accurate instrumented striker data in the future is expected to lead to valid and useful fracture toughness correlations.

Standardization Efforts

ASTM Task Group E28.07.08 on Miniature and Instrumented Notched Bar Testing was formed a little more than two years ago to develop two new standards. The first standard covers miniature notched bar impact testing and relies on many of the existing practices related to test machine requirements and verification as specified in existing standard E 23. The second standard is focused on instrumented testing. Upon acceptance of the standard by ASTM, both the existing E 23 and the new miniature notched bar standards would reference the instrumented impact standard. To date, both new standards have balloted twice



	Load (N)	Displacement (m)	Velocity (m/s)	Time (s)	Energy (N-m)
General Yield	1.477E+4	2.116E-4	5.420E+0	4.000E-5	2.259E+0
Peak Load	1.868E+4	2.092E-3	5.195E+0	3.930E-4	3.397E+1
Brittle Fracture	1.676E+4	2.792E-3	5.105E+0	5.290E-4	4.644E+1
Arrest Load	1.142E+4	2.940E-3	5.088E+0	5.580E-4	4.866E+1
Complete	-1.769E+	2.206E-2	4.786E+0	4.499E-3	7.886E+1

Figure 5: Attaching strain gages to the test machine striker enables measurement of the force during impact. Shown at left is a force-deflection response for a test conducted in the transition region.

at the subcommittee level and an instrumented/miniature specimen round robin test program is under way.

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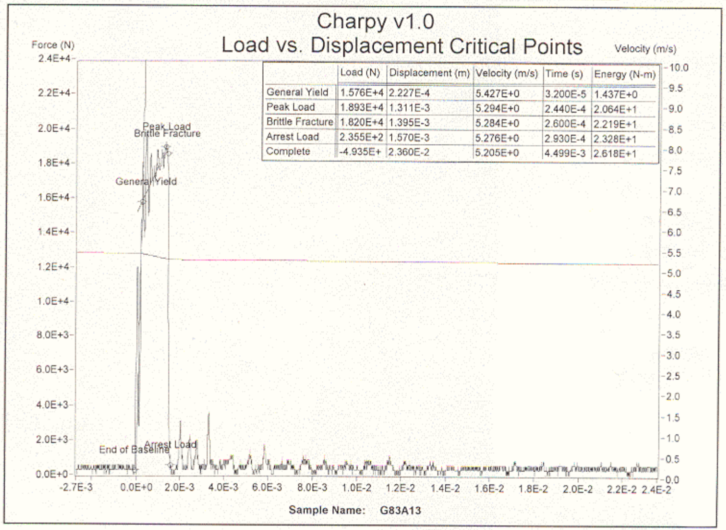
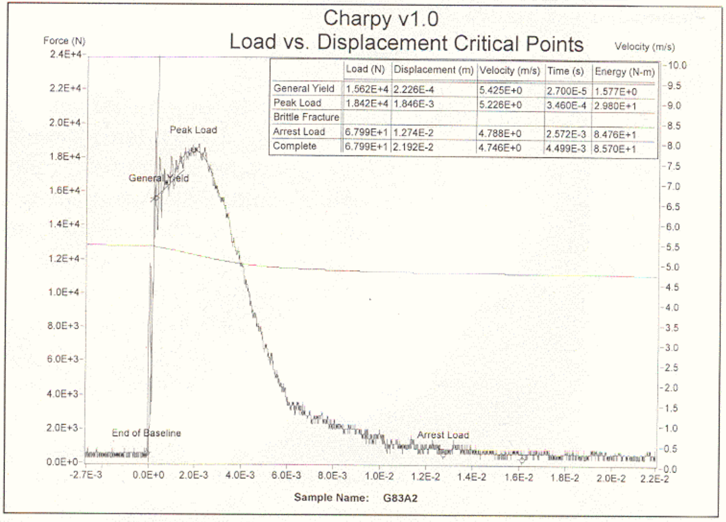
Shown at right: (upper figure) Force-Deflection Response for a Test Conducted at a Low Temperature Where the Material Exhibits Brittle Behavior.
(lower figure) Force-Deflection Response for a Test Conducted at High Temperature Where the Material Exhibits Ductile Behavior.



	Load (N)	Displacement (m)	Velocity (m/s)	Time (s)	Energy (N-m)
General Yield	1.576E+4	2.227E-4	5.427E+0	3.200E-5	1.437E+0
Peak Load	1.893E+4	1.311E-3	5.294E+0	2.440E-4	2.064E+1
Brittle Fracture	1.820E+4	1.395E-3	5.284E+0	2.600E-4	2.219E+1
Arrest Load	2.355E+2	1.570E-3	5.276E+0	2.930E-4	2.328E+1
Complete	-4.935E+	2.360E-2	5.205E+0	4.499E-3	2.618E+1



	Load (N)	Displacement (m)	Velocity (m/s)	Time (s)	Energy (N-m)
General Yield	1.562E+4	2.226E-4	5.425E+0	2.700E-5	1.577E+0
Peak Load	1.842E+4	1.846E-3	5.226E+0	3.460E-4	2.980E+1
Brittle Fracture					
Arrest Load	6.799E+1	1.274E-2	4.788E+0	2.572E-3	8.476E+1
Complete	6.799E+1	2.192E-2	4.746E+0	4.499E-3	8.570E+1