For 100 Years,

NOTCHED BAR IMPACT TESTING STANDARDS HAVE YIELDED WIDESPREAD BENEFITS FOR INDUSTRY

Without standardization, the impact test has little meaning. The test result obtained from an impact test is dependent upon the specimen size, notch geometry, and the geometry of the anvils and striker. To a lesser degree, impact test results are also dependent upon other variables such as impact velocity, energy lost to the test machine, and friction. The goal of those who have written and modified ASTM E 23, Standard Test Methods for Notched Bar Impact Testing of Metallic Materials, has been, and is, to standardize and control the variables associated with impact testing.

ASTM E 23 describes notched-bar impact testing of metallic materials by both the Charpy (simple-beam) and the Izod (cantilever-beam) methods. While for some materials the Izod method is used, the Charpy method is the overwhelming choice for metallic materials. Because it is the method of choice, ASTM E 23 and this paper give more attention to the Charpy method.

In the late 1800s and early 1900s, many different specimen and anvil geometries were being used for Charpy testing. As a result it was difficult, if not impossible, to correlate the results of various investigators, and the energy absorbed in fracturing a Charpy test specimen was in question. In 1909, Révillon concluded that standardizing the specimen and anvil geometries was necessary to obtain reproducible results and thus overcome the opposition to impact tests.[1] The first version of ASTM E 23 accomplished that. Various manufacturers of impact machines could now make machines that would produce test results similar to tests performed on their competitors' machines. Further revisions to ASTM E 23 strived to make the impact test result a more accurate measure of the energy required to fracture the specimen. These changes included: (1) modifications to the striker, (2) standardizing windage and friction losses and corrections, (3) standardizing test machine foundation requirements, (4) standardizing specimen supports and shrouds to reduce "jamming" of the broken specimen which falsely increases the measured energy, (5) standardizing the impact velocity, and (6) requiring verification specimens to be tested that can detect a variety of sources of test errors.

As these changes were made to ASTM E 23, manufacturers of impact test machines and users of the test methods were forced to change their designs and procedures in order to conform to the standard. As a result, impact tests performed today, in accordance with ASTM E 23, are reliable and reproducible throughout the world.

The Early Days of Impact Testing

The earliest known publication on the effects of impact loading on materials was a theoretical discussion by Tredgold in the early 1800s on the ability of cast iron to resist impulsive forces.[2] In 1849, the British formed a commission to study the use of iron in the railroad industry, which began its work by considering practical approaches to impact testing.[3] In 1857, Captain Rodman[3] devised a drop weight machine for characterization of gun steels, and over the subsequent 30 year period, this machine was widely used in the testing of railroad steels and for qualification of steel products. These early drop weight tests were conducted using smooth (no notch or crack starter) rectangular bars. While the test worked well for brittle materials, where initiating a crack is easy, ductile materials would only bend and inducing fracture was not possible. LeChatalier introduced the use of notched specimens while conducting drop weight tests in 1892.[4] 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. While the addition of a notch was a major improvement in the test method, a test procedure was needed that would provide a continuous, quantitative measure of the fracture resistance of materials.

Pendulum Impact Testing

A hundred years ago, in 1898, a report by Russell showed a machine that was based on the same swinging pendulum concept as those in common use today.[5] His report included data on many construction materials, and emphasized the effect of the rate of loading in evaluating materials for different service conditions. The pendulum impact machine of Russell finally provided a means for measuring the energy absorbed in fracturing a test specimen for a wide range of materials and conditions, from brittle at low test temperatures to ductile at high test temperatures.

Impact testing was an exciting and active research field near the turn of the century and a 1902 bibliography listed more than 100 recent papers on impact testing published in the United States, France, and Germany.[6] Such studies were compared and discussed at the meetings of the International Association for Testing Materials (IATM) (before ASTM took up this topic) during the next decade.[7,8] During this time frame, the committee members conducted research that overcame the shortcomings in the impact testing techniques, until they had developed robust and carefully considered procedures that provided useful information for industrial users. Even though these early standardized procedures were primitive by today's standards, they proved very satisfactory in evaluating the impact behavior of materials. For example, these early reports record that the test procedures were adopted by the French Navy for ship machinery, especially for engine shafting. Incidentally, it was a representative from France, G. Charpy, who became the chair of the impact testing activity after the 1906 IATM Congress in Brussels, and presided over some very lively discussions on whether impact testing procedures would ever be sufficiently reproducible to serve as a standard test method.[9] Although not the inventor of the pendulum impact test, Charpy's name is associated with the test because of his efforts to improve and standardize it.

Development of ASTM Method E 23

In about 1923, an ASTM subcommittee began to prepare a standard test method for pendulum impact testing. This effort took until 1933 when ASTM published "Tentative Methods of Impact Testing of Metallic Materials," ASTM designation E 23-33T. (An ASTM specification of "Tentative" indicated that it was subject to annual review and was a work in progress. The tentative designation is no longer used by ASTM.)

ASTM E 23-33T specified that a pendulum-type machine was to be used in testing and "recognized two methods of holding and striking the specimen," that is, the Charpy test and the Izod test. It did not specify the geometry of the striking edge (also known at the time as the "tup") for either test. It stated that "the Charpy type test may be made on unnotched specimens if indicated by the characteristics of the material being tested, but the Izod type test is not suitable for other than notched specimens." Only a V-notch was shown for the Charpy test. Although the dimensions for both types of specimens were identical with those currently specified, many tolerances were more restrictive. The units were shown as English preferred, metric optional. The authors pointed out many details that influence the test results, but because they did not have the knowledge and database needed to specify values and/or tolerances for these details, the document was issued as a tentative. The original document contains an appendix with general discussions of applications, the relation to service conditions, and comparisons between materials. As our understanding of the Charpy-test variables has grown, ASTM E 23 has been revised to incorporate the new knowledge.

The first revision was issued in 1934 and it added a dimension for the radii of the anvil and specifically stated that "these specimens (both the Charpy and the Izod) are not considered suitable for tests of cast iron" referencing a report of ASTM Committee A-3 on Cast Iron. The method retained the "tentative" designation.

The geometry of the Charpy striking tup, specifically the radius of the tup that contacted the specimen, was not specified in the 1934 revision, but the minutes of the 1939 and 1940 meetings for the Impact Subcommittee E1 state that this item was discussed and a survey was made of the geometries used in the United Kingdom and in France. Those countries used radii of 0.57 mm and 2 mm respectively. For reasons that were not recorded, the members of the Subcommittee agreed to a radius of 8 mm at the 1940 meeting and ASTM E 23 was revised and reissued as E 23-41T. Two other changes that occurred with this revision were that the metric units became the preferred units and keyhole and U notches were added for Charpy-test specimens.

Impact testing seems to have been a useful material evaluation technique, but was not a common requirement in purchase specifications and construction standards until the recognition of its ability to detect the ductile-to-brittle transition in steel. Probably the greatest single impetus toward implementation of impact testing in fabrication standards and material specifications

The subject of this third-place paper is ASTM E 23, Standard Test Methods for Notched Bar Impact Testing of Metallic Materials, which is under the jurisdiction of ASTM Committee E-28 on Mechanical Testing.

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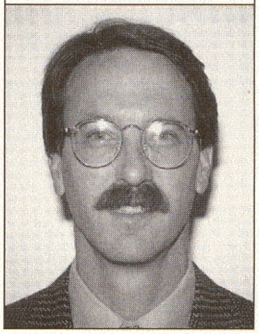

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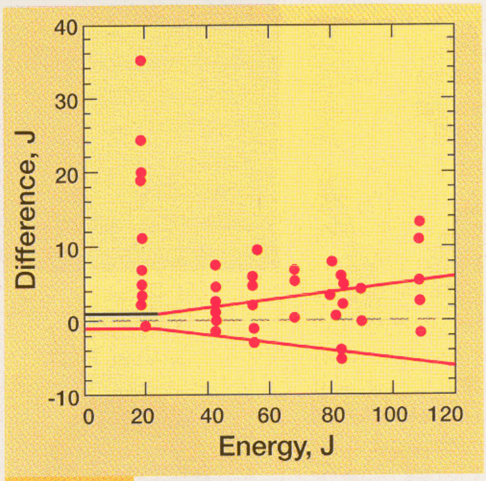

Figure 1: **The deviation and energy values obtained for the first round of tests on industrial machines.** The deviation is calculated as the difference between the results of the Watertown Arsenal machines and the industrial machines. This data was originally published by D.E. Driscoll, *Reproductibility of Charpy Impact Test*, ASTM STP 176, 1955.

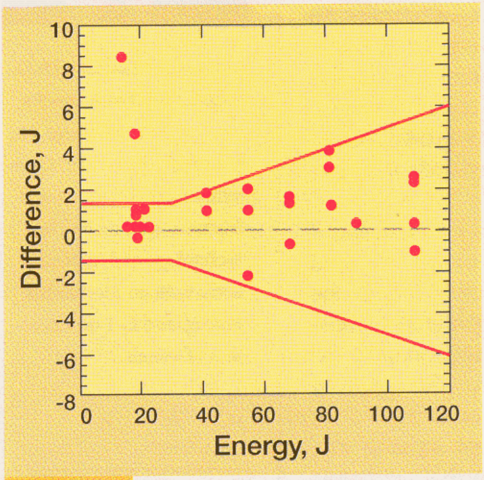

Figure 2: **The deviation and energy values for the second and third rounds of tests on industrial machines.** The data shows all but two of the machines tested were able to pass the 1.4 J or 5% criterion after appropriate repairs were made. This data was originally published by D.E. Driscoll, *Reproductibility of Charpy Impact Test*, ASTM STP 176, 1955.

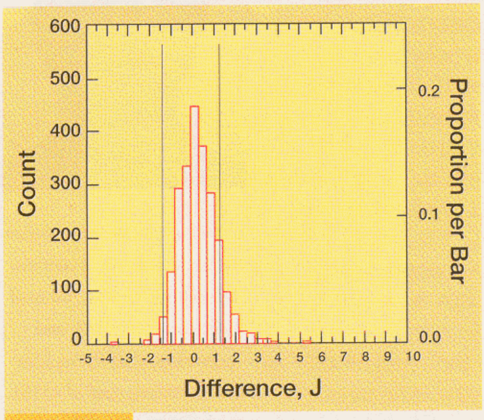

Figure 3: **Distribution of low energy verification data. Data for 1995-1997.** Approximately 2,400 tests, each test is an average of five specimens.

came as a result of the large number of ship failures that occurred during World War II. These problems were so severe that the secretary of the Navy convened a Board of Investigation to determine the causes and to make recommendations to correct them. The final report of this board summarized the magnitude of the problems found during this study.[10] Of 4,694 welded steel merchant ships studied from February 1942 to March 1946, 970 (over 20 percent) suffered some fractures that required repairs. The magnitudes of the fractures ranged from minor fractures that could be repaired during the next stop in port, to eight fractures that were sufficiently severe to force abandonment of these ships at sea. Also, at least 26 lives were lost because of these fractures. The total cost of these fractures to our nation (replacement and repair of ships, loss or delay of critical cargo needed for the war effort, and loss of lives) was immense.

The problem was complex and remedies included changes to the design, changes in the fabrication procedures, retrofits, as well as impact requirements on the materials of construction. Assurance that these remedies were successful is documented by the record of ship fractures that showed a consistent reduction in fracture events from over 130 per month in March 1944 to fewer than five per month in March 1946, even though the total number of these ships in the fleet increased from 2,600 to 4,400 during this same period.[10]

Benefits from the Introduction of Verification Testing

In 1948, many users felt that the scatter in the test results between individual machines could be reduced further, so additional work was started to more carefully specify the test method and the primary test parameters. By 1964, when the ASTM E 23 standard was revised to require indirect verification testing, the primary variables responsible for scatter in the test were well known. In a 1961 paper, Fahey[11] summarized the most significant causes of erroneous impact values as follows: (1) improper installation of the machine, (2) incorrect dimensions of the anvil supports and striking edge, (3) excessive friction in moving parts, (4) looseness of mating parts, (5) insufficient clearance be-tween the ends of the test specimen and the side supports, (6) poorly machined test specimens, and (7) improper cooling and testing techniques. While the machine tolerances and test techniques in ASTM E 23 addressed these variables, it was becoming apparent that the only sure method of determining the performance of a Charpy impact machine was to test it with standardized specimens (verification specimens).

Much of the work that showed impact tests did not have inherently high scatter, and could be used for acceptance testing, was done by Driscoll at the Watertown Arsenal.[12] Driscoll's study set the limits of 1 ft-lbf and ±5 percent, shown in Figures 1 and 2. The data superimposed on these limits in Figures 1 and 2 are the initial verification results gathered by Driscoll for industrial impact machines to evaluate his choice of verification limits. In Figure 1, the verification results for the first attempt on each machine are shown: only one machine fell within the ±1 ft-lbf limit proposed for the lower energy range. In Figure 2, results for re-tests on the same machines are shown, after maintenance. Driscoll's work showed the materials testing community that not all machines in service could perform well enough to meet the indirect verification requirements, but that most impact machines could meet the proposed requirements if the test was conducted carefully and the machine was in good working condition. With the adoption of verification testing, it could no longer be convincingly argued that the impact test had too much inherent scatter to be used as an acceptance test.

Early verification test results showed that 44 percent of the machines tested for the first time failed to meet the prescribed limits, and it was thought that as many as 50 percent of all the machines in use might fail.[13] However, the early testing also showed that the failure rate for impact machines would drop quickly as good machines were repaired, bad machines were retired, and more attention was paid to testing procedures. It was estimated that approximately 90 percent of the machines in use could meet the prescribed limits of ±1 ft-lbf or ±5 percent. Recently acquired verification specimen data, shown in Figures 3 through 5, confirms these predictions. Failure rates for verification tests at low, high, and super-high energy ranges are currently estimated to be 12, 7, and 10 percent respectively.[14]

Overall, the impact of incorporating verification limits in ASTM E 23 has greatly improved the performance of impact machines; data collected using ASTM E 23 machines can be compared with confidence. ASTM E 23 is still the only standard in the world, to our knowledge, that requires low energy impact tests for verification, and as shown by the data in Figure 1, results obtained using machines in need of maintenance can vary by more than 100 percent at the low energy level. In effect, the limits imposed by ASTM E 23 have produced a population of impact machines that are arguably the best impact machines for acceptance testing in the world.

Case Study in the Nuclear Industry

Notched bar impact data do not directly provide engineering data (such as plane strain fracture toughness 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. It is essential that a nuclear reactor be operated in a manner that ensures that the vessel integrity is maintained under both normal and transient operating conditions. In particular, the vessel must be protected from both brittle and ductile fracture. This is accomplished by postulating limiting flaws and using linear elastic fracture mechanics (LEFM) models to calculate the allowable coolant temperature (T) and pressure (P) during heat-up, cool-down, and leak/hydro testing (P-T curves). The P-T limits are revised periodically throughout the life of a plant to account for neutron damage to the pressure vessel. The Charpy shift, indexed at 41 J, is used to shift the ASME (American Society of Mechanical Engineers) reference stress intensity factor (K_{IR}) curve to account for the effects of neutron bombardment.

Since it is impractical to test large fracture toughness specimens throughout the life of a nuclear power plant, surveillance programs use Charpy and tensile specimens to track the neutron induced embrittlement. As illustrated in Figure 6, the nuclear industry uses the 41 J index to define a ductile-brittle transition temperature (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 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). In older plants built before fracture toughness testing was widely used, Charpy testing was used to qualify individual heats of material. The ASME code and the Code of Federal Regulations prescribe minimum plate properties that must be satisfied prior to service (e.g., at least 102 J of energy on the upper shelf prior to service). The NRC requires an in-depth fracture mechanics assessment if the Charpy USE is expected to drop below 68 J during the operating life of the plant.

It is difficult to include all the economic benefits realized by using the Charpy impact test in the nuclear industry. Nevertheless, some insight can be gained by noting that most utilities assess the outage cost and loss of revenue for a nuclear plant to be in the range of $300,000 to $500,000 per day. If Charpy data can be used to extend the life of a plant one year beyond the initial design life, a plant owner could realize revenues as large as $150,000,000. Further, the cost avoidance from a vessel-related fracture is expected to be in the billion-dollar range. To date, the NRC has shut down one U.S. plant as a result of Charpy data trends. It is important to note that this plant's pressure vessel was constructed from a one-of-a-kind steel and is not representative of the U.S. reactor fleet. Nonetheless, with decisions like this being based on the Charpy test, the importance of ASTM E 23 and the restraints it applies cannot be overemphasized.

Cost Saving in the Steel Industry

The Charpy V-notch (CVN) test specimen and associated test procedure is an effective cost-saving tool for the steel industry. The specimen is relatively easy to prepare, many specimens can be prepared at one time, various specimen orientations can be tested, and relatively low cost equipment is needed to test the specimen. In many structural steel applications, the CVN test can be used 1) as a quality control tool to differentiate heats of the same type of steel, 2) for quality assurance purposes, and 3) to predict service performance of components. Also, CVN test information can be correlated with fracture toughness data for a class of steels so that fracture mechanics analysis can be applied directly. One may question how all the above factors help a

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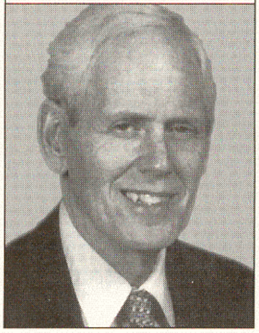

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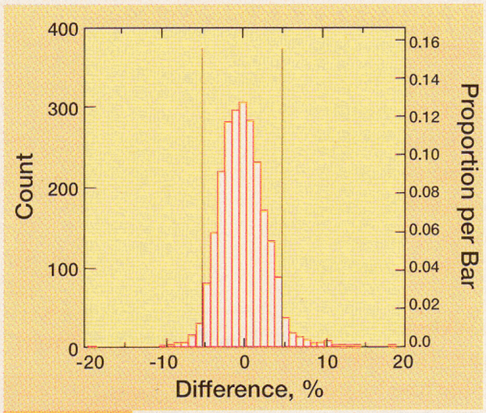

Figure 4: Distribution of high energy verification data. Data for 1995-1997. Approximately 2,400 tests, each test is an average of five specimens.

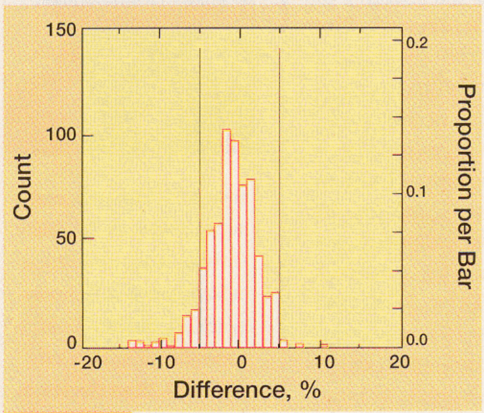

Figure 5: Distribution of the super-high energy verification data. Data for 1995-1997. Approximately 650 tests, each test is an average of five specimens.

steel producer sell a reliable product.

Consider the following case. A steel producer has a contract to supply plate steel for an offshore platform. The plate material needs to meet mechanical properties that are quite rigorous for safety and end product reliability reasons. Before full-scale production of the order can begin, the steel supplier needs to demonstrate to the buyer that the material is capable of meeting such criteria. To accomplish this, the supplier qualifies the material for the project. The process begins by making the steel grade and then testing a portion of the plate to determine if all required criteria are met. Steel mill equipment imposes limitations on plate size; therefore, individual steel plates need to be welded together in the field to produce lengths that can reach deep into ocean waters. Small sections of the sample plate are welded together and fracture mechanics tests are conducted to determine the crack tip opening displacement (CTOD) toughness in the heat affected zone (HAZ) and areas along the fusion line where the weld metal meets the base metal. Then, for example, a steel supplier might correlate the CTOD test results with CVN 50 percent ductile-brittle transition temperature (DBTT). By a-greement between the customer and supplier, this correlation can allow the steel supplier to use the Charpy test instead of the more expensive and time consuming CTOD testing.

One piece of information that can be used directly in design applications is the critical plane-strain stress-intensity, K_{Ic} value. It is defined as that value occurring ahead of a sharp crack at the moment of unstable crack propagation. The K_{Ic} value is related to component geometry, applied stress, and flaw size. Barsom and Rolfe[15] proposed a plane strain fracture toughness CVN energy correlation that can be used in the transition region:

$K_{Ic}{}^2 / E = 2(CVN)^{3/2}$ **(English units)**

where K_{Ic} is the plane strain fracture toughness, E is Young's modulus, and CVN is the absorbed energy value from the Charpy V-notch test.

If one knows the values of E and CVN (easily obtainable) for a given material, a quantitative assessment of permissible stress levels and critical flaw size can be calculated. It must be noted that the above equation was developed for a particular grade of steel and therefore may not be suitable for all grades of steel. However, the development of such

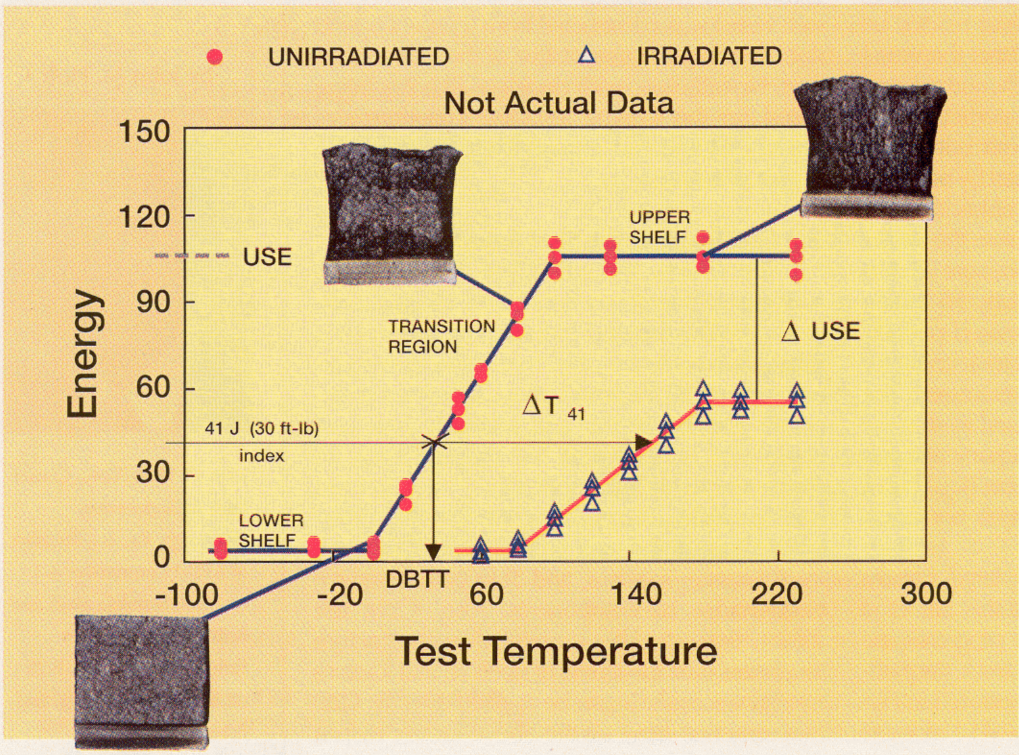

Figure 6:

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.

correlations for a particular class of steel can be very cost effective. As mentioned earlier, the nuclear industry has used Charpy parameters qualitatively to indicate the need for in-depth fracture mechanics analyses when the Charpy parameter falls below prescribed values. Design criteria for bridge steels have also been based on such correlative procedures.[16]

Continuing Standardization Efforts

Even after 100 years, the Charpy impact test procedures still have room for improvement. The ASTM E 23 standard has recently been redrafted to provide better organization and to include new methods such as in-situ heating and cooling of the test specimens. Two new related standards are also under development through ASTM Task Group E28.07.08 on Miniature and Instrumented Notched Bar Testing, which was formed a little more than two years ago. 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. Instrumented testing involves the use of strain gages that are attached to the striker. In this method, the force-deflection curve can be obtained for each test. Research is focused on using these data to obtain plane strain fracture toughness as well as other key test parameters. Upon acceptance of the standard by ASTM, both the existing E 23 standard and the new miniature notched bar standards would reference the instrumented impact standard.

Conclusion

As can be seen, the ASTM E 23 standard is a document that is improving with increasing technical knowledge. Several years ago, at the ASTM Symposium on the Charpy Impact Test: Factors and Variables, a bystander was overheard to say, "I see that there is a Symposium on the Charpy Test; what can be new there?"[17] Since then, the document has been updated twice and is currently being revised to reflect new developments and to make it more "user friendly."

Although ASTM E 23 is now a standard, and no longer tentative, it continues to be a "work in progress;" a work used extensively to help evaluate existing and new materials for products and structures—a test to ensure safety as well as to reduce the initial and life-of-structure costs. Knowledge is continually being gained that will help make the test more accurate and reliable. New technologies such as miniaturization of the test, instrumenting the striker to obtain additional data, and developing mechanics models to enable extraction of plane strain fracture toughness will be areas of development over the next 100 years. It is anticipated that the improvements to E 23 over the past 100 years will not overshadow the benefits that will be realized in the future.

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References

1 Louis Révillon, "The definition of Resilience in Impact Tests," Proceedings of the Vth Congress of the International Association for Testing Materials, Section III3, Copenhagen 1909

2 Tredgold T., "Strength of Cast Iron," pp 245 - 268, 1824

3 White A.E., Clark C.L., "Bibliography of Impact Testing," Department of Engineering Research, University of Michigan, 1925

4 LeChatalier A., "On the Fragility After Immersion in a Cold Fluid," French Testing Commission, Volume 3, 1892

5 Experiments with a New Machine for Testing Materials by Impact, S.B. Russell, Transactions ASCE, Vol 39, p. 237, June 1898.

6 Bibliography on Impact Tests and Impact Testing Machines, W.K. Hatt and E. Marburg, Proceedings ASTM, Vol. 2, p. 283, 1902.

7 Report on the Work of the Council from the Budapest to the Brussels Congress - 1901-1906, Proceedings of the International Association for Testing Materials, Brussels Congress, 1906.

8 Proceedings of the Sixth Congress of the International Association for Testing Materials, New York, 1912.

9 Report on Impact Tests of Metals, G. Charpy, Proceedings of the Vth Congress of the International Association for Testing Materials, Section III1, Copenhagen 1909.

10 The Design and Methods of Construction of Welded Steel Merchant Vessels: Final Report of a (U.S. Navy) Board of Investigation, Welding Journal, 26, 7, July 1947, p. 569.

11 N. H. Fahey, Effects of Variables in Charpy Impact Testing, Materials Research Standards, Vol 1, No. 11, Nov., 1961

12 D. E. Driscoll, Reproducibility of Charpy Impact Test, Impact Testing, ASTM STP 176, 1955

13 N. H. Fahey, The Charpy Impact Test - Its Accuracy and Factors Affecting Test Results, Impact Testing of Metals, ASTM STP 466, ASTM, 1970

14 C. N. McCowan, C. M. Wang, and D. P. Vigliotti, Summary of Charpy Impact Verification Data: 1994 - 1996, Submitted to the Journal of Testing and Evaluation, 1998.

15 J. M. Barsom and S. T. Rolfe, Eng. Frac. Mech., 2(4), 1971, p. 341.

16 ASM Metals Handbook, Ninth Edition, Vol. 8, 1985, pp. 263, 264.

17 Charpy Impact Test: Factors and Variables, ASTM STP 1072, J. M. Holt, editor, ASTM, 1990

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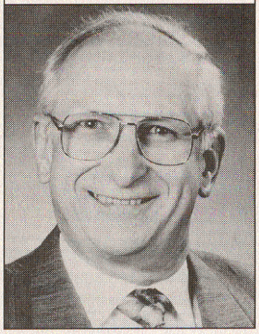

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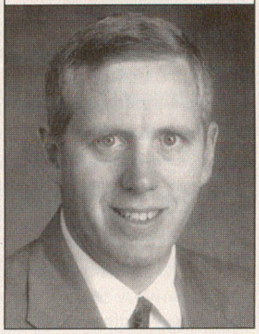

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