Pendulum Impact Machines

Procedures and Specimens

T. Siewert, M. Manahan, C. McCowan, Editors

STP 1476

INTERNATIONAL
Standards Worldwide

STP 1476

Pendulum Impact Machines: Procedures and Specimens

Thomas Siewert, Michael Manahan, and Christopher McCowan, editors

ASTM Stock Number: STP1476

ASTM International
100 Barr Harbor Drive
PO Box C700
West Conshohocken, PA 19428-2959

Printed in the U.S.A.

Library of Congress Cataloging-in-Publication Data

Pendulum impact machines : procedures and specimens / Thomas Siewert, Michael Manahan, and Christopher McCowan, editors.
p. cm. — (STP 1476)
ISBN 0-8031-3402-9 ISBN 978-0-8031-3402-7
1. Impact—Testing—Equipment and supplies. 2. Pendulum. 3. Notched bar testing—Equipment and supplies. I. Siewert, T. A. II. Manahan, Michael P., 1953– III. McCowan, C. N. (Christopher N.). IV. Series: ASTM special technical publication ; 1476.

TA418.34.P46 2006
620.1'125—dc22

2006016951

Peer Review Policy

Each paper published in this volume was evaluated by two peer reviewers and at least one editor. The authors addressed all of the reviewers' comments to the satisfaction of both the technical editor(s) and the ASTM International Committee on Publications.

The quality of the papers in this publication reflects not only the obvious efforts of the authors and the technical editor(s), but also the work of the peer reviewers. In keeping with long-standing publication practices, ASTM International maintains the anonymity of the peer reviewers. The ASTM International Committee on Publications acknowledges with appreciation their dedication and contribution of time and effort on behalf of ASTM International.

Printed in (to come)
Month, 2006 (to come)

Foreword

This publication consists primarily of the papers presented at the Second Symposium on Pendulum Impact Machines: Procedures and Specimens, sponsored by ASTM Committee E28 on Mechanical Testing and its Subcommittee E28.07 on Impact Testing. The Symposium was held on November 10, 2004 in Washington, D.C., in conjunction with the standards development meetings of Committee E-28. The Symposium was organized to commemorate the development of and rapid advancement of instrumented impact testing about 100 years ago, and to discuss some current issues.

This book includes the nine papers presented at the Symposium and another one submitted only for the proceedings (with lead author Vigliotti). The papers are organized into four sections by topic: Historical Developments in Impact Testing, Impact Test Procedures and Machine Effects, Reference Specimens, and Issues with Instrumented Strikers. The symposium was chaired jointly by Tom Siewert and Chris McCowan, of the National Institute of Standards and Technology, and Michael P. Manahan, Sr., of MPM Technologies, Inc.

Contents

SESSION IV: ISSUES WITH INSTRUMENTED STRIKERS

Overview

In the past, ASTM Subcommittee E28.07 (and its predecessor, E-1.7) has sponsored seven symposia on impact testing, published in Proceedings of the Twenty-Fifth Annual Meeting (1922), Proceedings of the Forty-First Annual Meeting (1938), STP 176 (1956), STP 466 (1970), STP 1072 (1990), STP 1248 (1995), and STP 1380 (1999). These symposia covered a broad range of topics and occurred rather infrequently, at least until 1990. The period before 1990 might be characterized as one in which the Charpy test procedure became broadly accepted and then changed very slowly. However, the last three symposia, "Charpy Impact Test: Factors and Variables", "Pendulum Impact Machines: Procedures and Specimens for Verification", and "Pendulum Impact Testing: A Century of Progress", were driven by new forces: a recognition within ISO Technical Committee 164 - Subcommittee 4 (Pendulum Impact) of some shortcomings in the procedure, and a growing interest in instrumented impact testing. These STPs (1072, 1248 and 1380), proved to be of interest to many general users of the test, but were of particular interest to the members of ASTM Subcommittee E28.07 (the subcommittee responsible for Standard E-23 on the Charpy test). During the past 15 years, the data presented at those Symposia have been the single most important factor in determining whether to change various requirements in Standard E-23. The data have also been useful in supporting tolerances and procedural details during the reballoting of ISO Standard 442 (now ISO 148-1) on Charpy testing, and in the refinement of instrumented impact test procedures.

Several years ago, the E28 Subcommittee on Symposia suggested that it was time to schedule another symposium on Charpy impact testing. Once again, we would bring together impact test researchers from around the world to share their latest discoveries and to provide input for further improvements in the test standards. We also discovered that instrumented impact testing was near its Centenary, and including a summary of the history seemed appropriate. In fact, the first paper reviews the very beginnings of instrumented impact testing, reported by Dunn in 1897 (an indirect method using a tuning fork, a light beam, optical film on a disk, and a "crusher gage") and a significant advance by Gargarin in 1912 (the direct and simultaneous measurement of force and displacement by use of a light beam, a low-mass mirror, and a spinning disk covered with optical film). Another paper on history traces the developments of impact test procedures over the past century. As noted in STP 1380, it seems as though the period of a century ago marked a time of the most rapid discovery and innovation in impact testing.

As in many of the previous symposia, the 2004 symposium was successful in attracting contributions from many countries. Because of its focus on measurement issues, the majority of the authors were from national measurement institutes and standardization societies.

The future of pendulum impact testing appears bright, as it continues to be specified in many construction codes and standards.

Acknowledgments

We appreciate the assistance of Committee E28, including both its Chairman, Earl Ruth, and its members, many of whom helped by chairing the sessions and recruiting abstracts.

Thomas Siewert
Christopher McCowan
National Institute of Standards and Technology

Michael Manahan
MPM Technologies, Inc.

SESSION I: HISTORICAL DEVELOPMENTS IN IMPACT TESTING

Journal of ASTM International, February 2006, Vol. 3, No. 2
Paper ID JAI12867
Available online at www.astm.org

Michael P. Manahan, Sr., Sc.D.[1] *and Thomas A. Siewert, Ph.D.*[2]

The History of Instrumented Impact Testing

ABSTRACT: Pendulum impact testing is widely known to have a history that extends back to the turn of the 20th century. To many researchers today, instrumentation of the impact test to acquire a load-time history, and thereby to provide important data in addition to absorbed energy, is usually considered to be a relatively recent development. However, our literature review has shown that starting from the earliest test machine development work, researchers have been interested in designing equipment capable of measuring both the energy expended in fracturing the specimen, and the force-deflection and energy-deflection curves. This paper recounts the early history of instrumented impact testing, and shows that it also extends back over 100 years. In fact, the earliest known paper on instrumented impact testing predates the first pendulum test machine publication by one year.

KEYWORDS: instrumented impact, history, force, deflection, absorbed energy, Charpy test

Introduction

In the early years of impact testing, researchers evaluated a wide variety of test systems and procedures in their search for both an understanding of the response of a material to impact loading and a method to quantify that response. Some sense of the early developments can be gleaned from papers by famous researchers such as Russell, Charpy, Fremont, Hadfield, Izod, and Martens [1–5]. Many of the papers by these authors reported results in terms of the absorbed energy, a simple and compelling way to rank the resistance to fracture. It offered a relatively reproducible and inexpensive method of comparing different materials and microstructural conditions.

However, not all researchers agree that the performance of a material for a particular application can be adequately assessed from the absorbed energy alone. Even 100 years ago, some researchers were convinced that force-time history data are needed to supplement absorbed energy. The earliest of these researchers did not have access to the sophisticated electronics that we use today for capturing the dynamic force history, but were able to develop innovative ways to record both the force and time data. This paper presents a history of some of the early developments from a key technology perspective. Rather than attempt to review all the early research, we have focused on a review of the important technology developments.

Background

Before reviewing the early instrumented impact technology history, a brief review of modern instrumented impact data acquisition and analysis will be helpful in understanding the early technical methods. In a typical application today, strain gages are attached to the striker and the voltage-time curve is measured during the impact (Fig. 1). The force-time curve is obtained from the voltage-time data using static calibration data. Knowing the mass of the striker, the acceleration-time curve can be numerically integrated to give the velocity-time curve (Fig. 2). The velocity-time curve can, in turn, be numerically integrated to give the displacement-time curve. These numerical integrations permit a force-displacement curve to be constructed. Since the work (or energy) of a system is the area under the force-displacement curve, the force-displacement data can be integrated to give the energy absorbed by the specimen in

Manuscript received October 25, 2004; accepted for publication August 30, 2005; published December 2005. Presented at ASTM Symposium on Pendulum Impact Machines: Procedures and Specimens on 8 November 2004 in Washington, DC; T. A. Siewert, M. P. Manahan, C. N. McCowan, and D. Vigliotti, Guest Editors.
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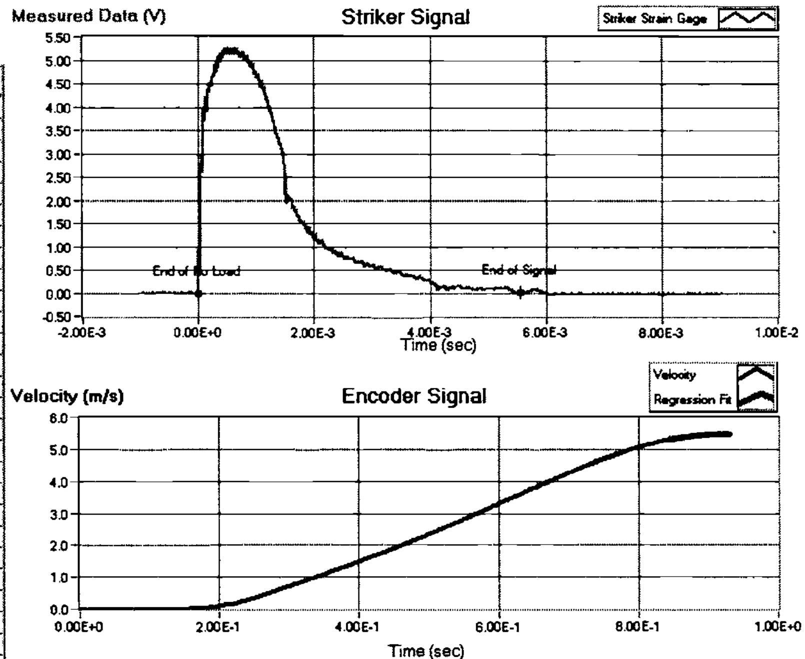
[2] NIST, Boulder, CO 80303.

Sample ID
ExampleData
Comments
System verify sample data

Impact^{TM} V5.0
Summary Report



Test Parameters	Value
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Temperature	20.0 °C
Oscilloscope	MPM Internal Oscilloscope
Striker Name	8mm Metals
Interpolation Method	Point-Point Linear
Encoder Controller	MPM Encoder System
Velocity Determination	Optical Encoder
Specimen Material	Metal
Specimen Type	Type A
Orientation	Isotropic
Notch Type	V Notch, no Side-Groove
Units Normalization	None
Energy Adjustment	1.0000
Length	55.00 mm
Width	10.00 mm
Thickness	10.00 mm
Span	40.00 mm
Uncracked Ligament	8.00 mm
Notch Radius	0.25 mm
Failure Type	Ductile / Brittle
Post Test Comments	Good Test
Impact Velocity	5.468 m/s
Striker Energy	188.306 N m
Dial Gage Energy	0.000 N m
Encoder Energy	188.594 N m
Striker Latch Angle	134.17°
Striker Final Angle	77.41°
Radius to COP	900.374 mm
Potential Energy	410.446 N m
Windage & Friction	1.543 N m
Percent Shear	88.00 %
Lateral Expansion	1.8618 mm

	Load (N)	Displacement (mm)	Velocity (m/s)	Time (s)	Energy (N m)
General Yield	1.7263E+4	3.971E-1	5.448E+0	7.190E-5	2.99992E+0
Peak Load	2.4398E+4	3.007E+0	5.051E+0	5.680E-4	8.00554E+1
Brittle Fracture	1.2958E+4	7.277E+0	4.368E+0	1.481E-3	1.48413E+2
Arrest Load	1.0008E+4	7.342E+0	4.360E+0	1.496E-3	1.49197E+2
End of Signal	6.0384E+1	2.395E+1	4.019E+0	5.545E-3	1.88306E+2

FIG. 1—*Strain gage voltage-time signal obtained with a modern instrumented striker system. The lower plot shows the striker velocity from release up to impact.*

fracturing. The four critical (or characteristic) force points are the general yield force (applicable to metals), maximum force, brittle fracture force, and brittle fracture arrest force (Fig. 3). The general yield force corresponds to yielding across the entire uncracked ligament. For ferritic materials 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.

An alternative to the current widely used approach of measuring the force (and integrating to obtain deflection), is the measurement of deflection. In cases in which the deflection is measured, differentiation is necessary to obtain the velocity-time and acceleration-time data. This approach is usually less desirable because of accuracy issues associated with differentiation of signal data. Nevertheless, early research focused on acquiring deflection data because of the measurement technologies available at that time.

The Earliest Paper: 1897

It is believed that the first technique to measure the incremental forces during impact loading is that reported by B.W. Dunn in 1897 [6]. Korber et al. [7] provided a review of instrumented impact test methods in 1926, and these authors also point to Dunn's work as being the first instrumented impact paper. It is interesting to note that Dunn's work was performed on a drop tower and his publication pre-dates that of Russell [1], who introduced the first pendulum impact machine for quantification of the total absorbed energy. In his introduction, Dunn describes how he had been frustrated with the inability to accurately measure the maximum pressure produced by the expansive force of exploded gun powder. At the time of Dunn's work, the common practice was to measure maximum explosive pressures using a "crusher gage," a cylinder of annealed copper that was inserted into the breech block and was compressed by a hard steel piston when the gunpowder ignited. The compression of the copper cylinder was evaluated after firing the gun by comparison to similar cylinders compressed to a similar deflection in a conventional tension/

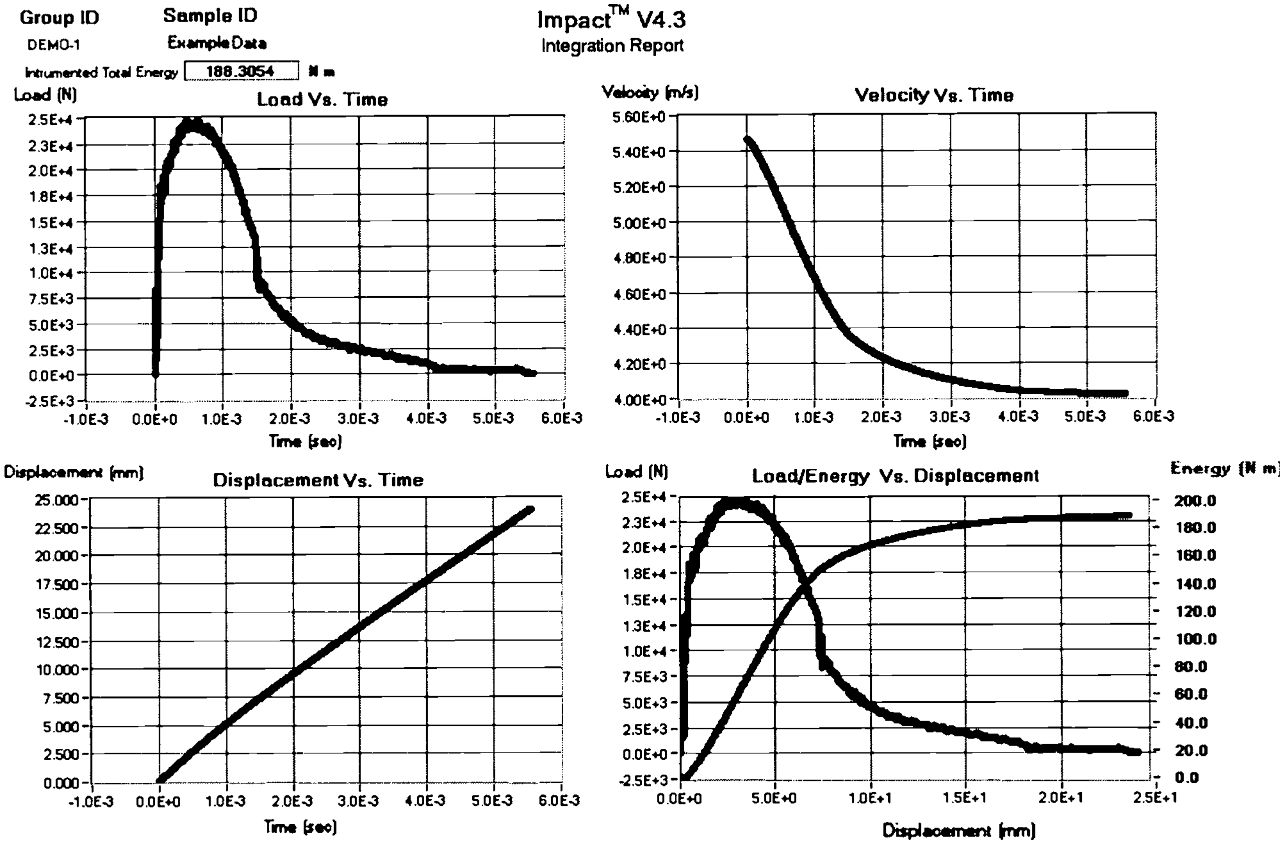
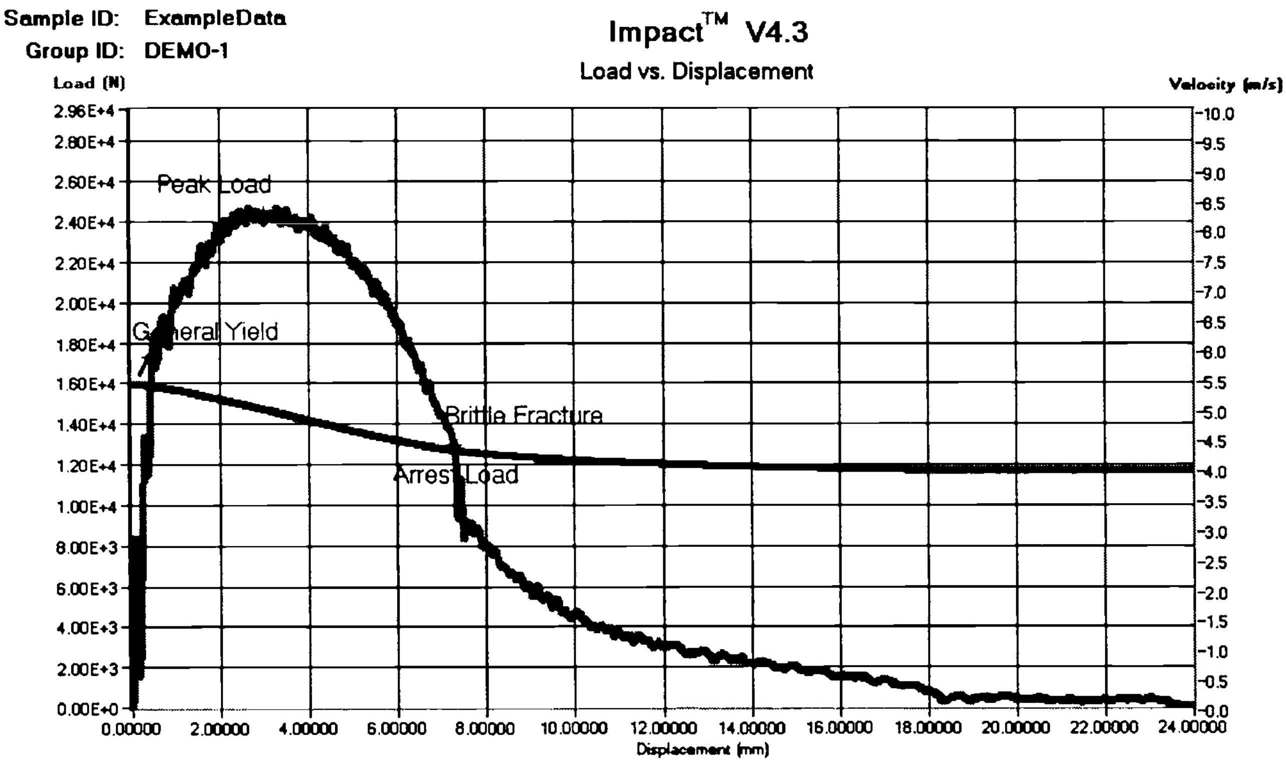


FIG. 2—*The raw voltage-time signal has been converted to the force-time signal through the striker calibration. The force-time curve is integrated to give the velocity-time curve. The velocity-time curve is integrated to give the striker displacement-time curve. Finally, the force-displacement curve is integrated to give the energy absorbed by the test specimen.*

compression testing machine. Dunn recognized that the use of static data to interpret dynamic compression of the copper cylinder was not correct, and he sought to obtain the equipment needed to measure the incremental strain. After a search for such equipment, he concluded that "no apparatus possessing the required delicacy and accuracy has been available" [6]. Therefore, in 1891, he conceived of a method for compressing copper cylinders dynamically while measuring the resistance to deformation.

His technique for deflection measurement involved mounting a small mirror on a hardened steel piston which rested on the copper cylinder. A weight was dropped on the piston and the mirror revolved about a fixed horizontal axis by linkage between the piston and mirror. As shown in Fig. 4, a beam of light was reflected from this mirror and impinged on a rapidly spinning drum covered with photographic film. By proper selection of geometric magnification (beam angles and distances) and rotation speed, he was able to obtain a very high-resolution record of the copper cylinder deflection.

To capture the time data, he modulated a second beam of light by the use of a hole cut through a tuning fork, and also focused this on the drum at a point directly under the beam from the mirror on the specimen. A schematic of the tuning fork arrangement from Dunn's paper is shown in Fig. 5, and the results of the measurements through a small aperture on the tuning fork are shown in Fig. 6. Proper selection of the tuning fork geometry permitted a wide range of time resolutions. Thus, the film had two traces, an upper trace that recorded the deformation of the cylinder, and a lower trace with transverse oscillations at the frequency of the tuning fork. As shown in Fig. 7, the final system was quite sophisticated with motion actuated introduction of the light beam so that the data record extended only over one third of the cylinder, even when it was spun at 100 revolutions per second. After the test, Dunn differentiated the deflection-time data to obtain the velocity and force data. In retrospect, we can see that one disadvantage of this system was the fact that the loading system for the cylinder started by resting against it. Another disadvantage was that the data analysis was time consuming and cumbersome. In addition, the mass (and thus the inertia) of the mirror, while slight, still limited the rate of response of the system. In spite of these problems, he was



	Load (N)	Displacement (mm)	Velocity (m/s)	Time (s)	Energy (N m)
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End of Signal	6.0384E+1	2.395E+1	4.019E+0	5.545E-3	1.88306E+2

FIG. 3—*This plot displays the force-displacement plot and the velocity-displacement plot. The characteristic forces, displacements, and energies are automatically determined.*

probably the first to plot quantitative force-time data from impact experiments, and the written discussion of his paper in a later issue of the journal included many favorable comments [8].

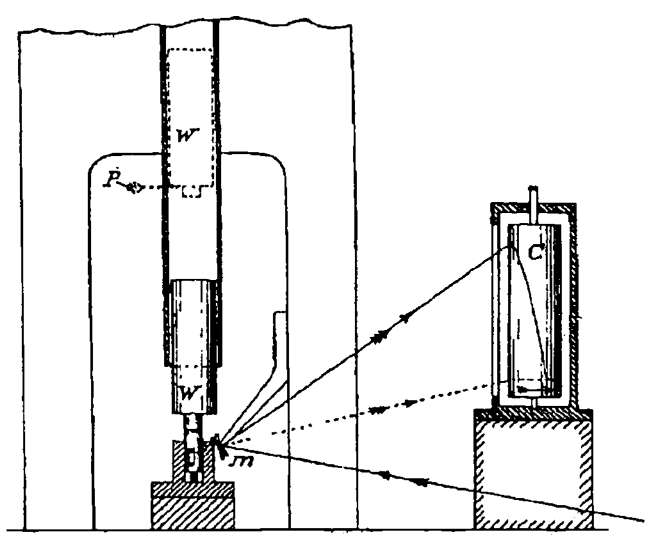

FIG. 4—*Schematic showing Dunn's method for measuring deflection data by projection of light onto a revolving photographic film [6].*

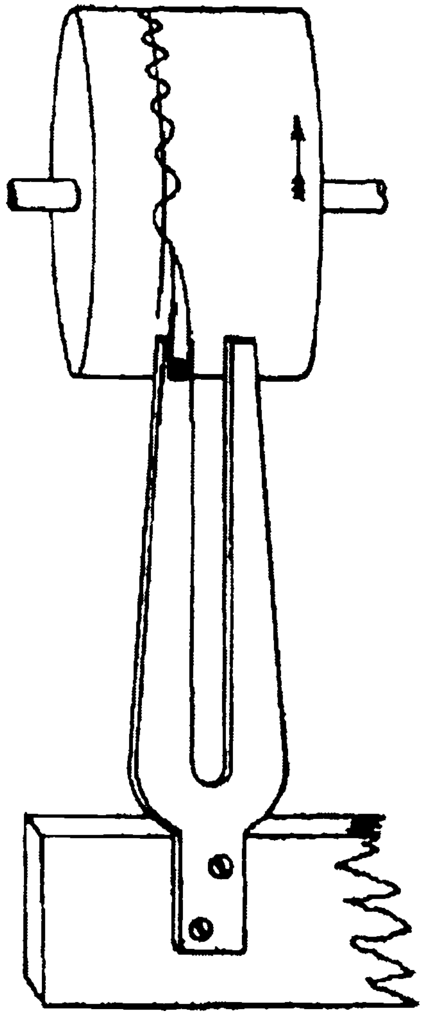

FIG. 5—*Dunn's original tuning fork arrangement for time measurement [6].*

Force and Deflection Measurement: 1897–1926

As previously mentioned, the intent of this review paper is to briefly summarize the significant technological developments in the early history of instrumented impact testing. Paper length limitations do not permit a review of all of the early literature. If the reader is interested in a more comprehensive review, Korber et al. [7] provide a detailed review of the work of several authors over the time period of 1897 to 1926. Many of these early papers are not reviewed here because they were incremental developments of the static comparison method. These authors impacted various steel shapes and compared the deformation with static measurements on the same geometry to estimate the peak force. In some cases, copper cylinders were placed between the test specimen and anvils and permanently deformed during impact. In other experiments, a hardened steel ball was pressed into a soft metal to characterize the peak force. An important limitation of these methods is that the comparison with static data assumes that the deformation is not dependent on the strain rate.

The next major step after Dunn's work seems to have been the development of simultaneous recording of force and deflection data by A. Gagarin, as reported in 1912 [9]. His paper summarizes the development (begun in 1904) of an apparatus that plotted deflection on one axis versus applied force on the other. His interest was in characterizing the response of the material to a known and controlled impact, instead of

FIG. 6—*Data obtained by Dunn passing light through a small aperture on the tuning fork [6].*

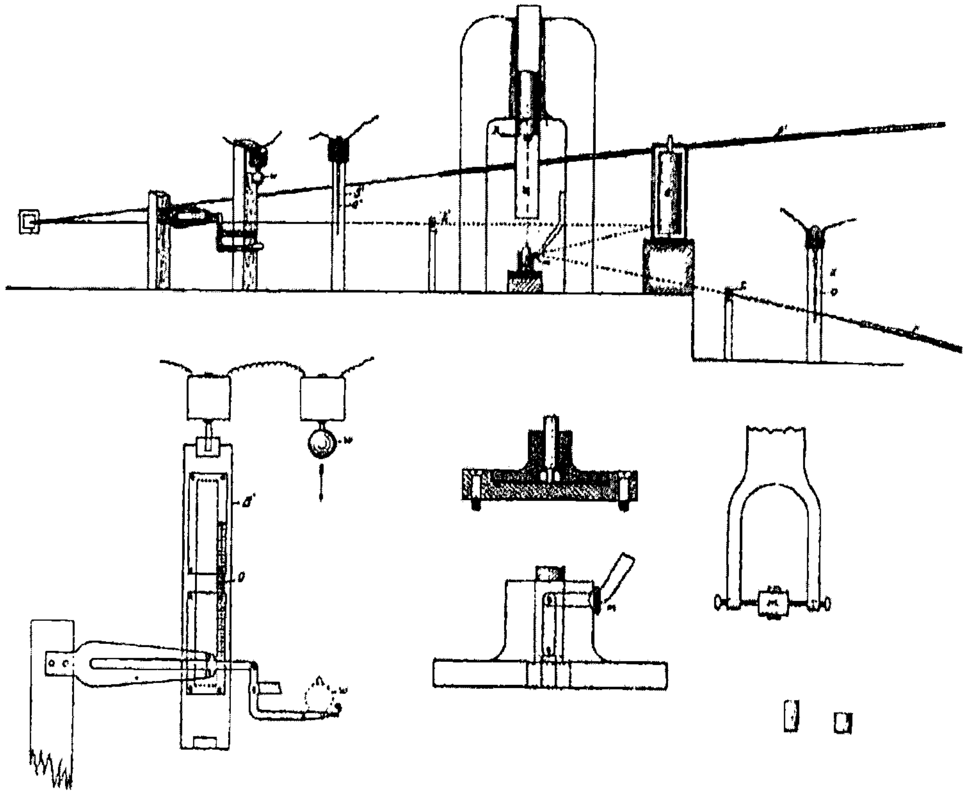

FIG. 7—*Schematic of Dunn's final experimental configuration [6].*

Dunn's more indirect interest in measuring the maximum pressure produced in a gun barrel. Therefore, Gagarin built a drop-weight machine equipped with a striker of mass at least 10 kg. Apparently, he was able to test a number of different specimen configurations including dynamic tensile and axial compression specimens (crusher gage copper cylinders). His original approach was to measure the force using a spring under axial compression. He constructed a needle and linkage in which the spring compression produced a vertical displacement of the needle and the extension of the test piece produced a simultaneous horizontal displacement of the needle. The force-deflection trace was etched on the surface of a thin sheet of lead. However, he was not pleased with the vibrations produced by the spring and decided to use low mass crusher cylinders for force measurement. While these cylinders were an improvement from a vibration perspective, the vibrations were not completely eliminated. His final improvement was to attach a mirror to the striker and use photographic film to measure the deflection of the test piece, as in Dunn's work. He did not present any final results from these experiments and concludes his paper stating, "At this point my experiments with a non-elastic dynamometer were interrupted."

During this time period, other researchers were focused on measurement of the displacement-time curve, from which the force-time curve was calculated by differentiation. In 1904, Hatt [10] reported results from experiments in which he attached a pen to the hammer of a drop tower and marked the surface of a drum spinning at constant speed. As reviewed in Ref. [7], several other researchers used similar methods to measure deflection-time data on a variety of specimens and materials. The spinning drum technique was initially applied by Hatt to long tensile rods to avoid the need for signal amplification. However, these tests often led to double necking. Testing of shorter specimens was accomplished using an optical imaging system. An interesting modification was introduced by Honiger [11]. He achieved optical magnification by creating a shadow of the back edge of the hammer, which was projected onto a light sensitive rotating drum. Using an appropriate lens, a blackened area was created on the film with an edge that provided the displacement-time curve.

Korber et al. [7] used a procedure similar to that of Honiger to achieve measurement of the pendulum displacement with minimized vibrations. This was done by machining a 0.1 mm vertical slit at the back edge of the hammer. An objective lens was used to project the light image of the slit to a fast rotating drum that was covered with light-sensitive paper (Fig. 8). The lens and light source positions were selected to give a 4× magnification of the hammer displacement.

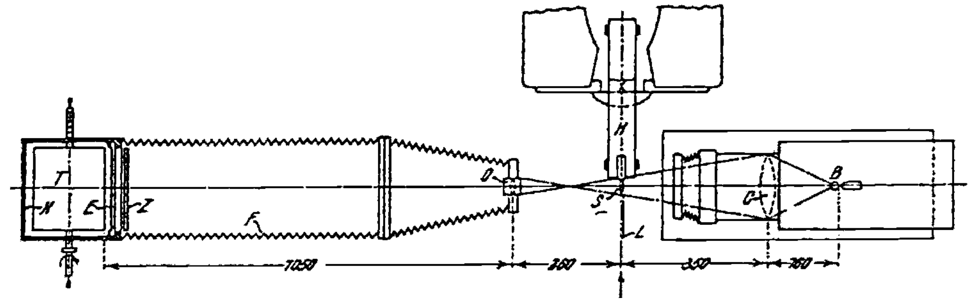

FIG. 8—*Schematic of experimental arrangement of Korber et al. for measurement of hammer deflection at 4× magnification [7].*

Piezoelectricity and Oscillographs: 1927–1930

Yamada [12] and Watanabe [13] performed significant work in Japan during this time period. Yamada was able to optically measure the change in velocity of the pendulum during contact with the test specimen. His work was an improvement over the work of Korber et al. [7]. As shown in Fig. 9, Yamada used a light source and a circular aluminum disk with 128 slits of 1 mm width machined along the circumference to produce a series of lines on a photographic plate attached to the striker. As the hammer slows due to contact with the specimen, the distance between the lines decreases and the change in velocity was measured. These data were then analyzed to give the force-deflection curves.

In 1929, Watanabe reported systematic instrumented impact studies using a C-hammer pendulum machine. As shown in Fig. 10, a piezoelectric load cell was constructed by attaching a quartz crystal under one of the test machine anvils. The load cell was calibrated statically and the effect of side loading due to specimens bending between the anvils was considered and shown to be small. A cathode ray oscilloscope was used to record the force-time data. The force-time data were integrated to yield the force-deflection curve. Impact tests on mild steel were performed and Watanabe studied various effects on the instrumented curve including velocity effects, notch radius effects, specimen thickness effects, and uncracked ligament effects.

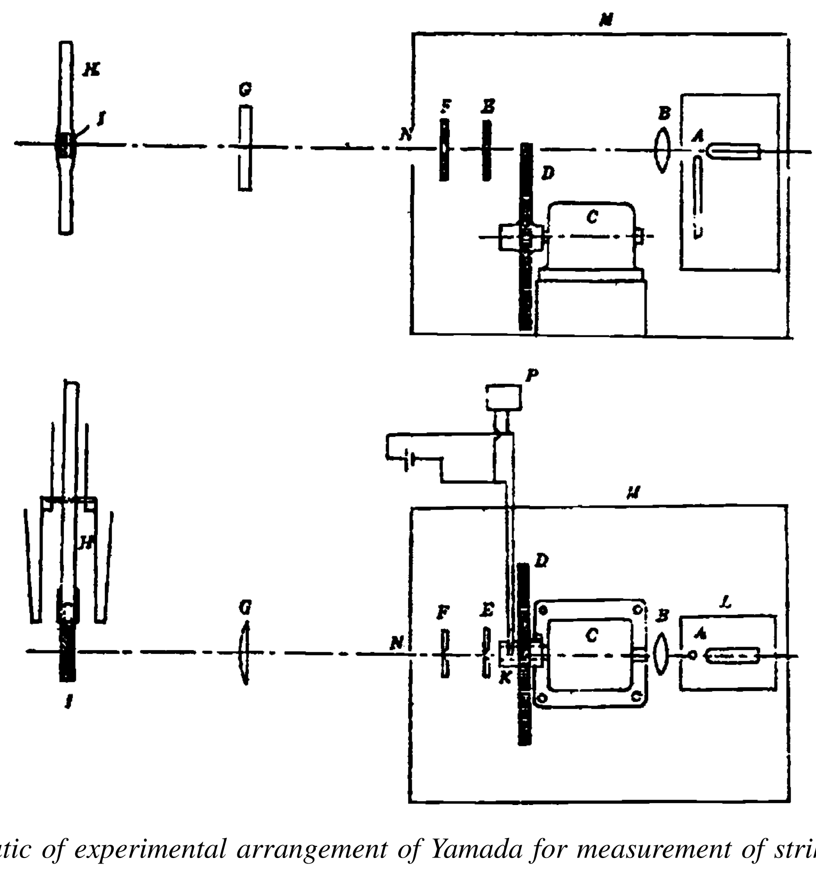

FIG. 9—*Schematic of experimental arrangement of Yamada for measurement of striker velocity [12].*

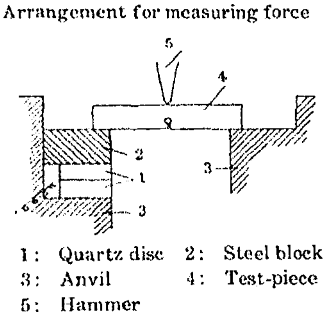

FIG. 10—*Schematic of Watanabe's piezoelectric load cell arrangement [13].*

Strain Gage Technology: 1930–1961

In 1958, Tanaka [14] reported on an improvement to Watanabe's piezoelectric load cell apparatus. Tanaka attached Rochelle salt crystals to the back of a C-hammer and measured the force-time response. That same year and at the same meeting, Ono [15] reported on the use of a strain gaged specimen support to measure the force-time response during impact on a pendulum machine. Ono used a vacuum tube amplifier to condition the signal for display on an oscilloscope. He used a light beam to trigger the data acquisition. In 1961, Sakui [16] reported on a similar arrangement, but the strain gages were attached to the C-hammer striker. Sakui studied the effects of annealing on the energy-test temperature and peak force-test temperature curves. Test configurations similar to Sakui are widely used today.

It is interesting to note that strain gage technology was available decades before it was applied in instrumented impact applications. While the true origin of the strain gage transducer is not known, Lord Kelvin reported on his work on strain-induced resistance changes in wires in the 1800s (Ref. [17]). In 1908, St. Lindeck of Germany introduced what many believe was the first bonded resistance strain gage wire transducer [17]. However, it was not until the 1950s that metallic foil bonded strain gages were introduced, and these rapidly replaced wire gages due to improvements in heat dissipation, creep reduction, better geometry control, and smaller sizes. This appears to have been the key technology improvement to pave the way for instrumented striker applications requiring small spaces for attachment.

Early 1960s to Present

From the early 1960s to the present time, there have not been any significant evolutions in the bonded resistance strain gage transducer technology other than miniaturization and performance improvements which resulted from the development and application of semiconductor gages and vapor deposited gages. On the other hand, significant technology advances on the data acquisition and analysis side have occurred, particularly over the past decade. Data acquisition systems are available today that are capable of acquiring 10^6 points over time ranges of a few microseconds to several seconds. These data are readily transferred to a personal computer and post-processed to produce data summary reports, as shown in Figs. 1–3.

Conclusion

The early literature recounts arguments about the relative importance of absorbed energy (in units of work) versus maximum intensity of the load (in units of force). Some of the researchers argued that both are important, and developed techniques to measure the force during successive increments of the fracture process. While the early work was conducted before the time of strain gages and electronic integration of the measured data, the early researchers were able to develop innovative photographic and mechanical methods to record the force for intervals shorter than one ten thousandth of a second. In most countries, the early study of impact forces was driven by military applications, but the results were eagerly adopted for infrastructure and manufacturing applications. As with the history of conventional (absorbed energy data) impact testing, many researchers from around the world contributed to the developments in the instrumentation of the test machine and in the understanding of the data. The original work was performed in the United States by an Army Lieutenant and then quickly spread to Europe. Significant advances came in the late 1920s in Japan, where piezoelectric methods and the use of oscillographs were developed. It was not until the late 1950s that strain gages, which are now widely used, were introduced for instrumented impact testing.

Acknowledgment

We appreciate the assistance of G. Lenkey of the Bay Zoltan Foundation for Applied Research, in providing the German review (Ref. [7]) that gave us several new sources of the early history.

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Journal of ASTM International, April 2006, Vol. 3, No. 4
Paper ID JAI12868
Available online at www.astm.org

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The Development of Procedures for Charpy Impact Testing

ABSTRACT: This paper provides a broad overview of the progress in procedural improvements for Charpy impact testing. It includes a short summary of early developments, a discussion of topics that have been the subject of recent research, and a description of the importance of direct and indirect verification procedures. The need for standard procedures was recognized soon after the test was developed, and the early discoveries help to build the framework for our current procedures. Nevertheless, even after all these years of procedure development, researchers still find the need to learn more about certain aspects of the test procedures. Recent research seems to be concentrated in several broad categories: properties of the specimen (e.g., surface finish, tolerances, and miniature sizes for special applications), the anvils and striker (e.g., radii and surface finish), and general test procedures (e.g., time to reach test temperature and suitability for cryogenic testing).

KEYWORDS: impact testing, international intercomparison, machine verification, specimen notching and conditioning, striker radius, test procedures, test temperatures

Introduction

For over 100 years, researchers have been trying to understand and to measure the effect of impact loading on the performance of engineering materials. Once researchers found that impact-test results improved their understanding of the performance of materials in service, they began to focus their attention on reducing the scatter in the test results. In fact, the development of consistent impact procedures was recognized to be of such importance that, even in 1912, Committee 26 (on impact testing) of the International Association for Testing Materials (IATM) summarized its main goals as to "fix the conditions to be fulfilled by two distinct tests in order that the results may be comparable and to correlate these numerically definite results to the qualities determining the practical values of a material for different uses" [1].

Since then, impact-test procedures and analysis methods have been refined as various researchers have discovered additional parameters that affect the test results. In some cases, these new results have been widely and uniformly adopted. In other cases, different standards organizations or machine manufacturers have chosen different approaches. As a result of many such choices by the different standards organizations over the years, we now find some variation in impact-test procedures around the world. Certainly, worldwide comparison of test data would be simplified if the procedures could be further harmonized between countries and between the various standards. The following section describes recent work directed toward understanding the effect of various procedural details. Publication of such work can persuade the various standards committees around the world to choose the best procedural details (that produce the most consistent results) or determine that some existing differences in procedures have no effect (so data developed under different procedures are considered equivalent and are mutually recognized).

Recent Research on Procedures

The four most common impact-test procedures in use around the world are probably ISO 148 "Steel—Charpy impact test (V-notch)," ASTM E 23 "Standard Test Methods for Notched Bar Impact Testing of Metallic Materials," EN 10045 "Charpy Impact Test for Metallic Materials," and JIS Z2242 "Method for Impact Test for Metallic Materials." While the four have some similarities, they also have differences. Much current research is directed toward both improving these (and other) standardized procedures, trying

Manuscript received September 27, 2004; accepted for publication August 17, 2005; published online March 2006. Presented at ASTM Symposium on Pendulum Impact Machines: Procedures and Specimens on 8 November 2004 in Washington, DC; T. A. Siewert, M. P. Manahan, C. N. McCowan, and D. Vigliotti, Guest Editors.

to understand the effect of their differences, and moving toward harmonization.

Striker Radius

Perhaps the aspect of the procedure that has been receiving the most study recently is that of striker radius. At least five papers in the past 15 years have investigated the differences between using strikers with radii of 2 and 8 mm.

In 1989, Fink [2] compared the results of a number of variables, including notch preparation and striker radii, on impact data. He studied a number of types of steel including 4340 (a heat-treatable tool steel used for 15 J and 120 J reference specimens), ASTM A 537 (a carbon-manganese steel used in pressure vessels), and HY-80 (a quenched-and-tempered high-strength steel). For these steels, he reported a nearly 1:1 relation for data generated with the two strikers, where the 2 mm striker produced results about 4 % higher. The precise relationship was

$$E_2 = (1.042)^{*}E_8 + 0.516 \quad (1)$$

where E_2 and E_8 are the energies of the 2 mm and 8 mm strikers and where the values are in units of ft-lbf. He reported a coefficient of correlation (r^2) of 0.9987 and a standard error of 1.36.

Also in 1989, Naniwa et al. [3] compared the results of impact machines with strikers of 2 and 8 mm radius using steels with a range of absorbed energies. Figure 3 in their report showed a 1:1 trend for the two striker radii up to about 200 J, then a gradual increase in the data of the 8 mm radius striker above the data of the 2 mm striker. When the machine with the 2 mm striker reported 300 J, the machine with the 8 mm striker reported about 400 J. Data for percent shear and lateral expansion showed no trend, and the shape of the transition curves was the same. Additional impact testing with instrumented strikers showed that both striker designs produced similar shapes for the first part of the record, but for the 8 mm radius striker the load was substantially higher near the end of the record. This suggested that the difference was occurring near the end of the loading cycle. Further testing (load measurements combined with imaging of the specimen in the anvils) on a static bending machine confirmed that the higher energy in the tail region occurred when the sides of the impact specimen made contact with the shoulder of the 8 mm striker. Thus, they attributed the difference between the two strikers solely to the greater width of the striker with 8 mm radius.

In 1995, Nanstad and Sokolov [4] evaluated the data from machines with 2 mm and 8 mm strikers using six different materials. They studied two heats of ASTM A 533 (a pressure vessel steel), a submerged arc weld with a high upper-shelf energy, a submerged arc weld with a low upper-shelf energy, a Russian Cr-Mo-V forging steel and two kinds of reference materials (4340 steel and a maraging steel). Although one plate showed lower values with the 8 mm striker and the other plate (and the low upper-shelf weld) showed lower values with the 2 mm striker, they concluded there was no clear trend (within one standard deviation) up to 175 J. Only the reference materials of highest energy (near 220 J) showed a clear difference, where the 8 mm striker produced energies about 11 % higher than those for the 2 mm striker.

Also in 1995, Siewert and Vigliotti [5] evaluated the data from two different brands of U-type pendulum machines, each with striker radii of both the 2 mm and 8 mm. They used reference-grade specimens at energies of 18, 45, 100, and 200 J. The small standard deviation produced by these specimens allowed a very precise measurement of machine or striker effects. They found very small differences between the two strikers for the three lower energy ranges, and an even smaller effect between the two brands of machines. At 200 J, they noted that the 8 mm striker produced energies about 10 J higher than those for the 2 mm striker, and the 2 mm striker produced standard deviations that were higher by about a factor of three.

These four studies suggest that the striker radius does not seem to be an important variable up to about 150 or 175 J, at least for the steels that were evaluated. However, above 200 J the two striker radii produce results that diverge as the energy increases. Ruth [6] has attempted to produce a compromise striker, one with the narrower profile of the 2 mm striker, but also with a flatter surface on the very front edge. This was accomplished by grinding the front to an 8 mm radius, then blending this surface to the edges by the use of a 1.5 mm radius. So far, this approach has not reached its goal.

Specimen Fabrication

Koester and Barcus [7] compared grinding and broaching of the notch. They found that both procedures produced data that were equally consistent, but there was a bias between the two techniques. They attributed this to differences in either the microstructural damage due to the notching or to slight imperfections in the notch radii.

Fink [2] also looked at notch production by grinding, broaching, and milling (with a fly cutter). He concluded that grinding the notch produces the smoothest and most consistent profile.

Direct Verification (Machine Condition and Mounting)—Schmieder [8] found that direct verification of a machine is not a simple task. He based much of his work on the concept that the permitted uncertainty of a metrological measurement must be ten times smaller than the tolerances specified for the device. In other words, he tried to use instruments and techniques that were more precise by an order of magnitude than that required by the standard, to develop a better estimate of how closely the machine approached the prescribed tolerance.

He evaluated four C-type pendulum machines and five U-type pendulum machines, spanning capacities from 3 to 250 J. He found that the losses due to friction and windage could exceed the permited limits on machines of very small capacity or on multi-range machines (where the bearings are sized for the highest capacity, and so have too much friction for the lower capacity). He also found that checking the difference between the center of strike and the center of percussion requires extremely accurate measurement of the period of the pendulum (as the center of percussion varies as the square of the period of the pendulum). At a 5 degree angle of swing, the friction would damp the swing before enough cycles would occur. At higher angles, the nonlinear terms became important, and even the use of elliptic integrals in the analysis was unable to correct for these effects.

Schmieder et al. [9] later studied the effect of various machine dimensions, including: tilted anvils, thinner anvils (striker contacting anvils 5 mm past the normal position), and striker not contacting the specimen opposite the notch. All these were studied at levels in excess of the variation permitted by ASTM Standard E 23, and all variations noticeably increased the absorbed energies. Thus, these data support keeping the machine tolerances that are specified by E 23.

Porro et al. [10] studied the use of compliance to evaluate the quality of the machine mounting, in terms of such common problems as loose bolts on the base of anvils, or paint or other low friction materials under the base.

Ruth et al. [11] studied the effect of surface finish of the machine anvils and striker. They found that surfaces smoother than those required by the standard procedures better simulate the surfaces of these parts after a period of use. Thus, a better finish will reduce the discontinuity in apparent energies when these parts are replaced.

Ruth et al. [11] also studied the effect of radius on the corners of the 8 mm striker, because wear can rapidly exceed a 0.25 mm tolerance. He found that increasing this radius to 0.5 mm had little or no effect, but increasing the radius to 1 mm had a very strong effect on the energy.

Yamaguchi et al. [12] studied the effect of anvil radius and taper. They reported a measurable reduction in absorbed energy as the taper angle is increased from 9 to 12 degrees, and a 5 % change in energy as the anvil radius is increased from 1 to 1.5 mm.

Specimen Size and Dimension Effects

Alexander and Klueh [13] compared Charpy specimens of standard size (10 mm by 10 mm) to specimens of half and third size. They found that the smaller specimens allowed more specimens to be produced from a given amount of material (especially important for irradiated materials), but produced different upper-shelf energies and different transition temperatures. They concluded that the upper-shelf energies could be corrected with a simple volumetric normalization procedure, but the shift in transition temperature was more complex. Later, Alexander et al. [14] revisited this issue and developed sub-size verification specimens that could be used to verify the performance of machines used to test sub-size specimens.

Manahan et al. [15] also looked at sub-size specimens, and developed a test machine design. They proposed a minimum cross section of 5 mm by 5 mm, and recommended side grooves to increase the amount of material in these smaller sections that is exposed to plane strain conditions.

Marsh [16] studied the effect of changing the tolerance on the right angle between the two 10 mm faces of the specimen. He varied the angles outside of the tolerance of 10 min of arc and found that greater variations produced statistically significant changes in the energies, especially for specimens with absorbed energies near 100 J. He concluded that a tolerance of 10 min on the right angles should be maintained.

Test Temperatures and Specimen Conditioning

Nanstad et al. [17] studied the effect of thermal conditioning, the process of bringing the specimen to the desired test temperature. They investigated a number of media including water, oil, acetone, and methanol at temperatures above and below ambient. They found that water was a poor choice between 50 and 100 °C because evaporative cooling is so significant that the specimen may cool below the temperature tolerance even if the specimen is broken within 5 s of leaving the bath. Also, they found that soaking times used with gaseous media need to be increased to ensure that the specimen has reached equilibrium.

The growing use of cryogenic magnets has promoted the use of impact testing to measure the ductile-brittle transition of structural materials at temperatures down to 4 K. Tobler et al. [18] offer several cautions. They found that the very low specific heat of metals below 77 K causes the specimens to heat rapidly as they are transferred from the bath to the anvils. For this reason alone, valid tests cannot be performed according to the procedures of Standard E 23. Further, even cooling the specimen in place in the anvils is unable to provide accurate data, as the work hardening during the initiation and propagation of the crack raises the temperature substantially. Thus they concluded that pendulum impact testing is not valid below 77 K, and any attempt to correlate performance from specimens cooled to 4 K is confounded by the variations in work-hardening rates in the various materials.

Manahan [19] reported that conditioning of the specimen when on the machine anvil and in position for testing (by use of a special fixture) reduces the changes in temperature that can occur when a specimen is transferred from a conditioning bath to the anvils. In addition, this procedure doubles the precision in centering the specimen in relation to the striker, since there is no rush to position the specimen.

Other Procedure Details

Sundqvist and Chai [20] reported on the production of in-house standard specimens (from a stable nickel-based alloy) for tracking the performance of an impact machine between the formal reverifications required by standards. They found that this was an excellent method of tracking the performance of machines that are used to test specimens made of materials that induce excessive wear of the striker and anvils.

In spite of the widespread use of notched specimens for evaluating material performance, Galban et al. [21] reported that unnotched specimens can provide standard deviations as small as, or smaller than, notched specimens of the same material. Since verification of machine performance is separate from evaluation of material performance, use of such specimens (with low standard deviations) could reduce the cost of the verification specimens.

Comparison of Data—Machine-to-Machine and Country-to-Country

Several recent round-robins or comparisons of national reference machines confirm that today's Charpy test procedures are at least as reproducible as those reported by Driscoll [22] in 1955, and are consistent between countries. These recent round robins have shown that the certified energies of verification specimens distributed by national metrological authorities usually agree within 1 % with the values determined by other national authorities. A 1998 study [23] compared the four organizations or laboratories that were found to certify the verification specimens for Charpy impact machines. These organizations were the Institute for Reference Materials and Measurements (IRMM, in Belgium), Laboratoire National D'Essais (LNE, in France), National Institute for Standards and Technology (NIST, in the United States), and National Research Laboratory for Metals (NRLM, in Japan). The study involved a comparison of the 2 and 8 mm radius strikers, three absorbed energy levels, and a large number of replicate tests for each of these conditions at each of these organizations. This study concluded that the other organizations developed average energies very close to those assigned by the laboratory that produced them, the specimens produced by the four organizations have similar spread in the data (coefficient of variations between 0.02 and

0.04), and the 2 and 8 mm radius strikers produced similar results for 4340 steel (absorbed energies below 200 J). Therefore, in spite of the various differences in procedures between the major standards in use around the world, the basic test procedure is quite reproducible, so the results developed in different countries and on different designs of (verified, high-quality) machines can be compared with confidence.

A follow-on three-year study [24] has just been completed and is reported in another presentation.

Machine Installation

The data obtained from a machine are not reliable unless the machine is mounted properly. NIST has published a Technical Note to help users to achieve an adequate mount [25]. The following is a summary of our recommendations.

The recommended foundation is a block of high-strength concrete measuring about 1.5-m long by 1-m wide by 0.5-m thick. Usually this requires cutting a hole in the floor to accommodate the new foundation. If other equipment in the area could affect the machine operation, you may want to isolate it from the floor with expansion-joint material.

Hold-down bolts used to secure the machine to the foundation should be of the inverted "T" or "J" type, and should be embedded in the concrete. The bolts, nuts, and washers should have a high strength (for example, AISI grade 8 or higher). NIST machines were mounted with 22-mm diameter grade 8 threaded rod, cut into pieces that were about 600-mm long. Then, 150-mm long pieces of the same threaded rod were welded to the end of the 610 mm (24 in.) pieces to make inverted "T" bolts.

After 72 h of curing, the machines were positioned over the foundation (supported by nuts on the rods) and leveled to a tolerance of 3:1000. The critical leveling procedure was done using the four nuts under the machine. After the machine was leveled, the outside of the nuts were wrapped with duct-seal putty to facilitate their removal from the "T" bolts later in the process. Then, the base was grouted and the machine was left in this position for 72 h.

After 72 h, the machine was lifted off the "T" bolts one last time. The putty was removed from around the nuts, the machine was repositioned on the "T" bolts and the nuts were torqued to about 500 N-m.

Direct Verification

This section explains direct verification requirements (based on those in ASTM Standard E 23), which confirm that a machine is in good operating condition, without the use of verification specimens. The direct verification tests are physics-based tests, which assure that the machine is functioning as closely as possible to a simple pendulum, with only small losses, due to friction and windage. Direct verification is most important when the machine is first installed or when major parts are replaced, but is also important during the periodic reinspections. While these tests are required for the periodic reinspection in ASTM E 23, NIST recommends that the free-swing test and windage-and-friction test be performed each day that the machine is used. The records of these tests then serve as a convenient measure of bearing performance. The following recommendations also come from a Technical Note distributed by NIST [25]. Space limitations prevented including illustrations of these characteristics here. The illustrations are available in the Technical Note.

Since the Charpy test is a dynamic test with vibration and impact loads, the hold-down bolts may loosen over time. In extreme cases, this may introduce error sufficient to cause a machine to exceed the tolerance limits of the indirect verification test. In marginal cases, the movement may still be sufficient to add a bias to the results that reduces the likelihood of passing. The tightness of all bolts should be checked periodically, especially the anvil bolts, the striker bolts, and the base-plate bolts. The manufacturer can supply the torque values for the anvil and striker bolts. The base-plate bolts should be torqued to the recommended torque values for the grade and size of the nuts and bolts. Only "J" or "T" bolts should be used; lag-type bolts can lead to errors. These are made to withstand only static loads. We believe that in some cases, the insert portion of lag bolts can loosen in the concrete. When lag bolts are retightened, they can pull out of the concrete and be pulled against the base of the machine, giving the impression of a properly mounted machine. This condition is very difficult to detect. A machine with this problem will exhibit erroneously high energy values at the low-energy level. The mounting procedure used to eliminate this problem for the NIST Master Reference Machines was described in the previous section.

Standard E 23 describes a routine check procedure that should be performed weekly. It consists of a free-swing check and a friction-and-windage check. The free swing is a quick and simple test to determine whether the dial or readout is performing accurately. A proper zero reading after one swing from the latched position is required on a machine that is equipped with a compensated dial. Some machines are equipped with a non-compensated dial. Such a dial is one on which the indicator cannot be adjusted to read zero after one free swing. The user should understand the procedure for dealing with a noncompensated dial. This information should be available from the manufacturer.

The friction-and-windage test assesses the condition of the bearings. The pendulum should be released and allowed to swing 10 half cycles (5 full swings). (The release mechanism should be held down this whole time to avoid additional friction when the pendulum swings back up to where it may push on the latch.) As the pendulum starts its 11th half swing, the pointer should be reset to about 5 % of the scale capacity. Record the actual value and divide by the 11 half swings. Divide this number by the machine range capacity, then multiply by 100. Any loss of more than 0.4 % of the machine capacity is excessive, and the bearings should be inspected.

Keeping a daily log or shift log with the machine is also recommended. The log can be used to track the zero and friction values. The log can also include information such as number of tests, materials tested, maintenance, and any other useful comments.

The anvil and striker radii should be carefully inspected for damage and for proper dimensions. Damage (chips or burrs) can be detected easily by visual inspection and by running a finger over the radii to check for smoothness. Measurement of the dimensions requires more sophisticated equipment. Radius gages are usually inadequate to measure the critical radii. Making molds of the radii (such as with silicone rubber) or making an indentation in a soft, ductile material (such as annealed pure aluminum), then measuring the impressions on an optical comparator is recommended. Occasionally even a new set of anvils and striker may have incorrect radii. Thus, new anvils and strikers should always be inspected before being installed in the machine. Since the radii will not have local wear before use (the radii are consistent along their length), they can be measured directly on an optical comparator or other optical measurement system.

Indirect Verification

Indirect verification uses carefully characterized test specimens to stress the test machine components to levels similar to those experienced during routine usage. Since many machine problems, such as loose anvils or striker, cannot be detected during direct verification, indirect verification serves as an important supplemental test of the machine performance.

Some reference specimens are designed to be tested at −40°C (−40°F) and some at room temperature. Since the absorbed energy changes with temperature, accurate temperature control is necessary to obtain valid test data. The temperature indicator should be calibrated immediately before testing. Ice water (0°C) and dry ice in ethyl alcohol (−78.5°C) are very convenient calibration media.

Post-Fracture Examination

Just matching the reference energies is not sufficient to confirm that the machine is fully satisfactory. For example, worn anvils can combine with high-friction bearings to compensate for each other and produce an artificially correct value during the verification test. These are called compensating errors. Unfortunately, these errors compensate only over part of the range, so the machine produces generally inaccurate values. The post-fracture examination of standardized verification specimens is a good way to identify such effects. Therefore, the NIST verification specimens come with a questionnaire (with critical questions about the machine and the test procedure) and a mailing label so the specimens can be returned to NIST. All specimens are examined and compared to the data on the questionnaire before a response is sent to the customers.

Following are the most common of the problems observed during examination of fractured specimens. In many cases, suggestions on how to correct or avoid them in the future are included.

Worn Anvils

Most of the wear of an impact test machine occurs on the anvils and striker. This wear can be evaluated by examining the gouge marks that are formed on the sides of high-energy specimens when they are forced through the anvils. Anvils that are within the required tolerance of the standard will make a thin, even gouge mark all the way across both pieces of the broken specimen. As the anvils wear, they will make a wider, smeared mark across the specimen halves. When wide, smeared marks are observed on a customer's specimens, the anvils should be changed, because the reduction in energy needed to push the specimens through worn anvils eventually drops the machine below the lower tolerance in the energy range. You can monitor the wear on your machine by retaining some specimens that are tested with new anvils and comparing them to specimens of similar composition and hardness that are tested as the anvils wear. For specimens at a similar absorbed energy, the gouge marks will grow wider and smoother as the anvils wear.

Off-Center Specimen

An off-center specimen strike occurs when a specimen is not centered against the anvils, so the striker contacts the specimen to the side of the notch. The low-energy specimen best indicates when an off-center strike occurs. This condition can be identified on the specimens by finding that the gouge marks caused by the anvils are not equidistant from the machined notch edges, and the striker gouge mark is offset the same amount from the notch. Also, the fracture surface of a correctly tested low-energy specimen is flat and both halves are even. However, the fracture surfaces of a specimen that has been tested off-center are on an angle. The more off-center the strike, the steeper the angle will be. This problem increases the energy needed to fracture a specimen. The most common causes for this slipping are worn or damaged centering tongs, a worn or misaligned machine centering device, careless test procedures, or the use of a cooling fluid that is too viscous at the test temperature (which causes the specimen to float on the specimen supports). Most machine manufacturers should be able to provide new centering tongs. Ethyl alcohol seems to be one of the best cooling media because it evaporates quickly from the bottom of the specimen to prevent specimen floating.

Off-Center Striker

This differs from the off-center specimen in that the specimen is centered against the anvils so the anvil gouge marks are equidistant from the machined notch edges. However, the striker does not contact the specimen precisely opposite the notch. An off-center striker is usually attributed to the pendulum shaft shifting off center. This shift can be the result of a loose alignment ring on the shaft or a loose bearing block on the machine. This problem also increases the energy needed to fracture specimens at all energy levels.

Uneven Anvil Marks

Frequent testing of subsize specimens can cause the anvils to wear unevenly. Since this wear is restricted to only a fraction of the area that the full-size reference specimen contacts, there is usually no effect on the energy required to fracture the specimen. This anvil condition presents two problems. First, since subsize wear is usually not indicated by a change in the energy required to break a reference specimen, inspection of the broken specimen is required. This wear will cause the anvils to be out of tolerance according to the requirements in the standard. This means that the machine does not meet the direct verification requirements of the standard, and is therefore not eligible for the indirect verification process. The second, and more important, problem is that the subsize specimens are being tested in an area of the anvil that is worn. When the wear is substantial, this condition will produce artificially low energy values for the subsize specimens. The anvils should be replaced on a machine with this condition.

Chipped Anvils

Sometimes an anvil can be chipped. Lower-energy specimens are affected the least amount because they are the hardest specimens and therefore have a more brittle fracture. High-energy specimens will produce higher than normal energy results and very-high-energy specimens are affected most by a chipped anvil. This condition should be detected easily by a visual inspection before using the machine. When an anvil is chipped, it must be replaced by a new anvil.

Anvil Relief

Some manufacturers of Charpy machines have designed a machined relief at the bottom of the anvil. This anvil design does not meet the direct verification requirements of ASTM Standard E 23. The relief increases the energy for high and very-high-energy specimens. It can also cause twisting of the specimens during fracture, which may also contribute to energy values higher than normal at all energy levels. However, this feature does not appear to add an excessive amount of energy to the test. (The results are usually within the allowed tolerances.)

Damaged Anvils

Under some test conditions, usually for elevated-temperature testing, the anvils can wear to a rough finish that creates excessive friction. This damaged condition is detected best on higher energy specimens. Rough anvils usually cause the gouge marks to become wider and push the specimen material to form a ridge that can easily be detected with the fingernail. This damage usually causes artificially high energy results. Damaged anvils must be replaced.

Bent Pendulum

A pendulum bent in the direction of the swing produces gouge marks on a specimen. This gouge mark is usually deeper on the top edge of the specimen as it sits in the machine. The striker contacts the top edge of the specimen first, causing excessive tumbling and twisting. This excessive activity can cause the specimen to interact with the striker or the pendulum after fracture and create additional energy loss. A bent pendulum can be detected by placing an unbroken reference specimen in the machine and placing a piece of carbon paper on the surface opposite the notch. At this point, lightly tap the striker against the specimen. This will make a mark on the specimen that can be inspected. If the pendulum is not bent, the mark should appear the same width across the specimen. If the pendulum is bent, the mark will be wider at one edge and become thinner or even not visible at the other edge. A new pendulum should be installed on such a machine to correct this problem.

Summary of Indirect Verification

Some aspects of Charpy machine condition and accuracy can be assessed only through the use of reference specimens. Further, some machine problems cause artificially low results, while other machine problems cause artificially high results. In addition, deviations in procedures can cause similar results. These machine problems and procedural deviations may go undetected for years without some sort of physical check. For this reason, examination of the broken specimens is a critical part of the verification process. Many machine problems can be avoided or corrected with the information presented in this paper. Also, suggested changes in procedure can help to ensure a successful test. Verification specimens are available from various organizations around the world, including:

- the Institute for Reference Materials and Measurements (IRMM, in Belgium),
- Laboratoire National D'Essais (LNE, in France),
- National Institute for Standards and Technology (NIST, in the United States), and
- National Research Laboratory for Metals (NRLM, in Japan).

Summary

1. Recent refinements in the procedures continue to improve the accuracy of the test. Topical areas include the striker, anvils, specimens, and temperatures.
2. The Charpy scales used by the various NMIs are consistent, and the current round-robin promises further harmonization of the various procedures.
3. The history of past international interactions shows that a free and open interchange of ideas between countries is of benefit to all.
4. Direct and indirect verification testing is needed to ensure the validity of data developed on a Charpy impact machine.

Acknowledgments

We appreciate the contributions of Dan Vigliotti, formerly of NIST, to the procedures used to evaluate verification specimens.

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SESSION II: IMPACT TEST PROCEDURES AND MACHINE EFFECTS

Journal of ASTM International, September 2005, Vol. 2, No. 8
Paper ID JAI12875
Available online at www.astm.org

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Effects of Removing and Replacing an 8-MM Charpy Striker on Absorbed Energy

ABSTRACT: It has been thought that removing and replacing an in-tolerance 8-mm striker may affect the results of a Charpy test. This thought brought about a requirement in Standard Test Method E23 [1] that states that if a striker is removed and replaced on a Charpy machine, the indirect verification is void and a new verification test must be performed. Groups of NIST SRM 2092 and SRM 2096 specimens were tested on machines with three different striker-mounting designs. The specimens were tested with the striker removed and replaced between groups. The results of these tests support a change in the standard that can make removing and replacing the striker acceptable without performing a new indirect verification test.

KEYWORDS: charpy, indirect verification, Izod, striker

Introduction

ASTM Standard Test Method E23 requires a Charpy machine to be indirectly verified once yearly. The indirect verification is performed by testing verification specimens. Upon a successful verification test, report of conformance is issued for the machine. This report states that the machine meets the indirect verification requirements of the standard. The standard states that a Charpy machine must be indirectly verified immediately after replacing parts that may affect the measured energy. It has long been believed that removing and replacing the striker will affect the results of a machine. It is true that when an out-of-tolerance striker is replaced with an in-tolerance striker, the results of the machine will be affected at higher energy levels. However, this work demonstrates that when an in tolerance striker is removed and replaced, the machine results are not affected as long as the striker is replaced properly. The mounting area of the machine must be free of rust and debris for a striker to be replaced properly.

For a Charpy machine to test Izod specimens, the Charpy striker must be removed and an Izod striker must be installed. When the Izod testing is completed and it is time to return the machine to Charpy testing, the Izod striker must be removed and the Charpy striker must be reinstalled. A Charpy machine owner may also have the opportunity to perform Charpy testing using a 2-mm striker. To perform the 2-mm testing, the 8-mm striker must be removed. After the 2-mm testing is completed, the 8-mm striker must be reinstalled. In both of the above cases, the standard requires the Charpy machine owner to perform a new indirect verification test. This requirement is costly to the machine owner and not necessary.

The purpose of this research is to provide a basis for a change in the standard that will allow removing and replacing an in-tolerance striker without performing a new indirect verification. This change will result in a cost savings for machine owners.

Manuscript received 8 October 2004; accepted for publication 22 February 2005; published September 2005. Presented at ASTM Symposium on Pendulum Impact Machines: Procedures and Specimens on 8 November 2004 in Washington, DC.

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Test Procedure

The research consisted of testing NIST SRM low and high-energy specimens on three Charpy machines located at NIST, Boulder, Colorado. The machines used were a Tinius Olsen machine with a capacity of 407 Joules, a Satec machine with a capacity of 407 Joules, and a Tokyo Koki machine with a capacity of 360 Joules. The Tinius Olsen and Satec machines are equipped with a "U" type pendulum and the Tokyo Koki machine is equipped with a "C" type pendulum. Figure 1 shows the difference between pendulum designs.

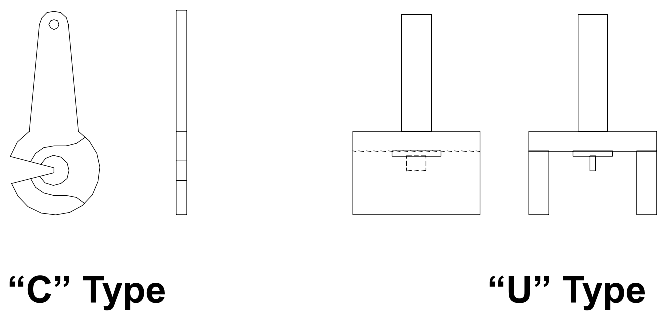

FIG. 1—*Machine pendulum designs*.

The striker is the part of the pendulum that contacts the specimen during the fracture event. The striker is mounted differently on each type of pendulum. The Tinius Olsen machine is equipped with a striker that uses four mounting bolts and is pinned for alignment. The pinned configuration assures that the striker is aligned properly. The Satec striker uses four mounting bolts. An alignment tool must be used to align the striker. The Tokyo Koki machine is equipped with a "C" type pendulum that uses keyways for alignment. The keyways assure that the striker is aligned properly.

NIST SRM LL-96 low-energy level specimens were used in this study. Five specimens were tested and compared to the certified value previously determined. The average of these five specimens was used to confirm that the machine compared with the original certified value. The striker was then removed and replaced. Five additional specimens were tested after the striker was replaced. The striker was removed and replaced three additional times with five specimens tested each time. The average of each set of five specimens was compared to the base line average. This same procedure was used to test NIST SRM HH-98 high-energy level specimens.

Results

For the purpose of this study, the machines are labeled 1, 2, and 3. Table 1 and Fig. 2 show the average of each set of five specimens at the low energy level. The average of the initial test and the second striker change of machine number 1 are outside of the acceptable range of the certified value (± 1.4 Joules). The average of the specimens tested after the fourth striker change on machine number 2 was out of the acceptable range. All other tests on machine number 2 were acceptable. There may be many reasons to explain the unacceptable averages produced by machines 1 and 2. However, they are not relevant to the subject of this research. The comparison of the results of the initial test to the results of the striker changes is more relevant than comparing the results to the Certified Value.

TABLE 1— *RM 2092 LL-96 low energy (J)*.

Machine Number	Certified Value	Initial Test	Striker Changes			
			1	2	3	4
1	16.0	14.2*	14.9	14.3*	14.9	15.3
2	16.0	16.8	17.4	16.9	6.2	17.6
3	16.0	16.3	16.3	16.2	16.6	16.6

*Out of Range (Acceptable Range is ± 1.4 Joules of Certified Value)

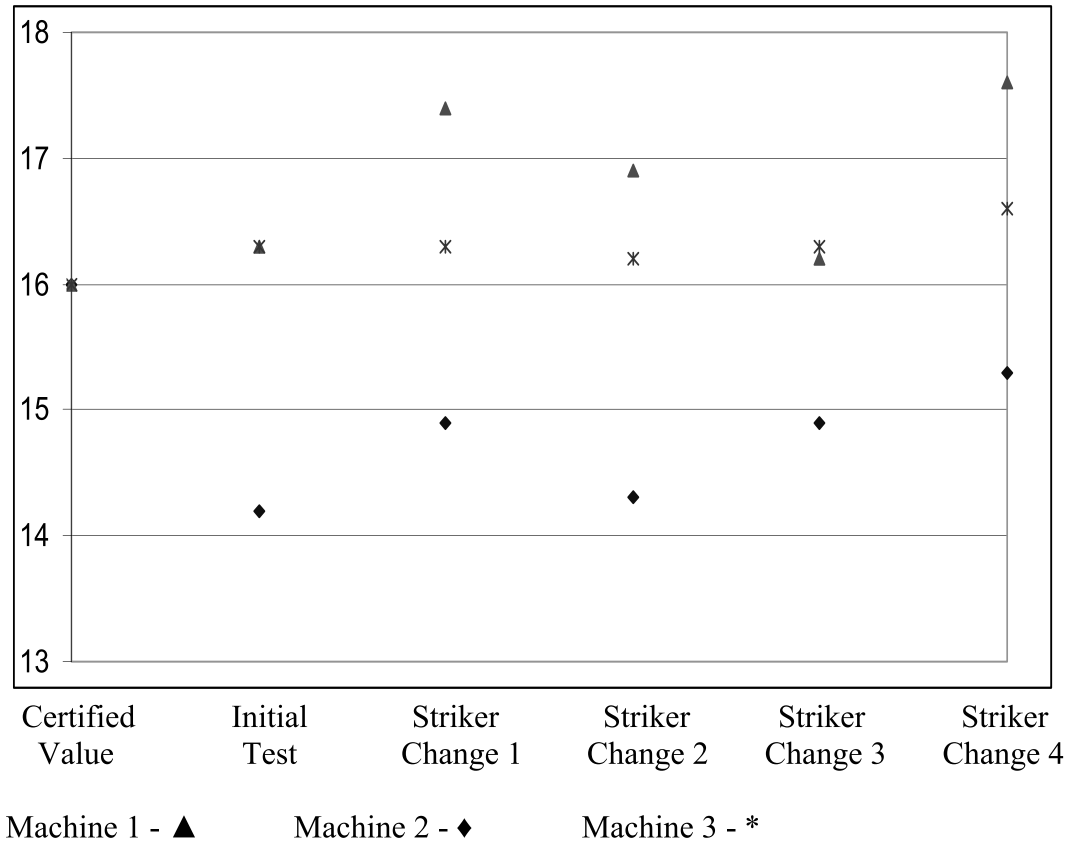

FIG. 2—*SRM 2092 LL-96 low energy (J).*

Table 2 and Figure 3 show the average of each set of five specimens at the high-energy level. The average of each set of five specimens tested on all machines fell within the acceptable range of the certified value.

TABLE 2—*SRM 2096 HH-98 high energy (J)*.

Machine	Certified Value	Initial Test	Striker Changes			
			1	2	3	4
1	105.7	106.3	105.0	107.8	106.8	108.0
2	105.7	107.7	109.7	108.2	106.8	106.8
3	105.7	102.3	105.4	104.4	102.8	103.8

Acceptable Range is ± 5 % of Certified Value

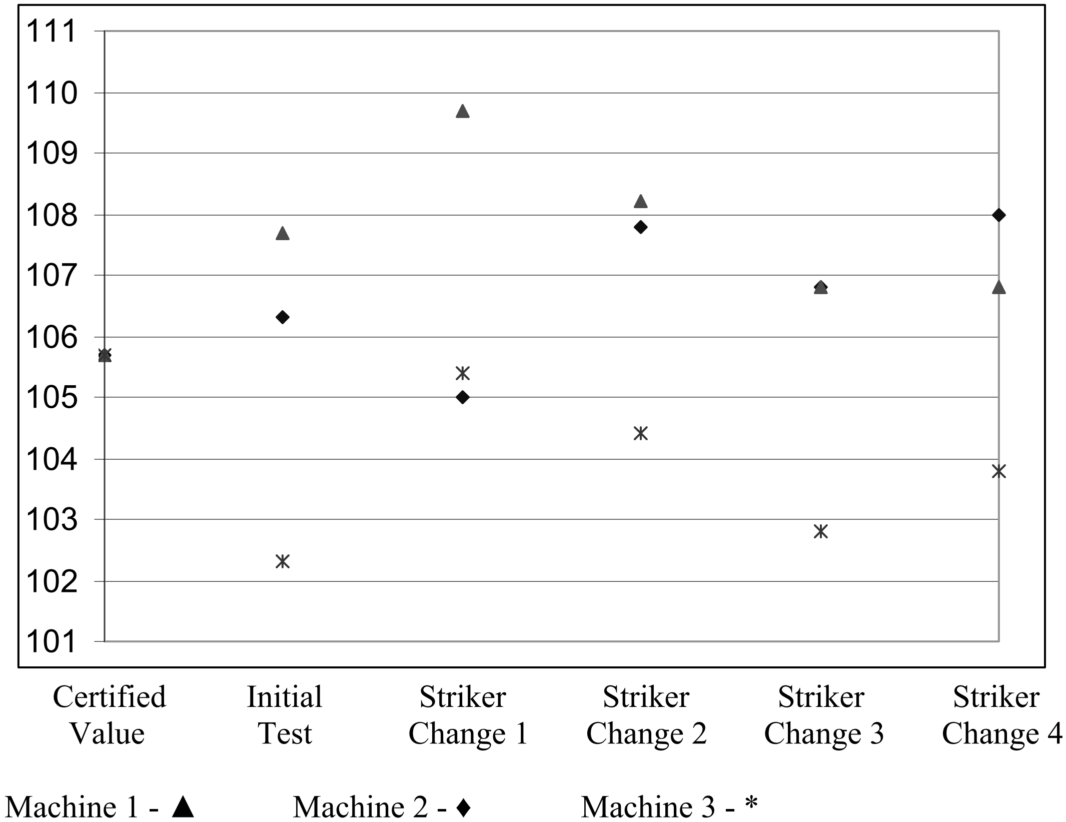

FIG. 3—*SRM 2096 HH-98 high energy (J).*

Conclusions

Removing and replacing an in-tolerance striker does not affect the performance of a machine as long as the striker is reinstalled correctly being careful to remove rust and debris from the mounting area and carefully mounting the striker according to the manufacturer's instructions. Standard Test Method E23 can be changed to allow the removal and replacement of an in-tolerance striker. This change will provide more flexibility to machine owners and allow them to use their machines more cost effectively. No similar work could be found to reference.

Reference

[1] ASTM Standard E 23, "Standard Test Method for Notched Bar Impact Testing of Metallic Materials," *Annual Book of ASTM Standards*, Vol. 03.01, ASTM International, West Conshohocken, PA, 2002.

SESSION III: REFERENCE SPECIMENS

Journal of ASTM International, February 2006, Vol. 3, No. 2
Paper ID JAI12869
Available online at www.astm.org

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International Comparison of Impact Reference Materials (2004)[7]

ABSTRACT: A three-year horizontal comparison has been completed between national laboratories that certify specimens for the indirect verification of Charpy impact test machines. The participants in this study were the Institute for Reference Materials and Measurements of the European Commission, the National Metrology Institute of Japan (NMIJ)[8], the National Institute of Standards and Technology in the United States, and the Laboratoire National d'Essais in France. The comparison was conducted to evaluate the impact of reference specimens over a three-year period. Sets of certified reference specimens, at low (15 J), medium (30 J), and high energy (100 J) levels were produced and distributed at the start of the study. Specimens were tested approximately every six months on each of the machines in the study. The results of the testing are presented and the stability of the various impact machines and specimens are discussed.

KEYWORDS: ASTM E-23, Charpy V-notch, EN 10045 impact testing, ISO 148 machine verification

Introduction

Charpy impact testing is often specified as an acceptance test for structural materials, and companies performing acceptance tests are typically required to verify the performance of their impact machine with certified reference materials. The laboratories in this comparison each have impact machines that play a role in the certification of reference materials for the verification of Charpy impact machines: (1) The European Commission Joint Research Centre, Institute for Reference Materials and Measurements (IRMM, Belgium), (2) Laboratoire National D'Essais (LNE, France), (3) The National Institute of Standards and Technology (NIST, USA), and (4) The National Metrology Institute of Japan (NMIJ, Japan). Annually, these four laboratories supply specimens to verify the performance of about 2000 impact machines around the world.

The purpose of this interlaboratory study is to determine the long-term stability of impact verification specimens and reference machines. We also examine the nominal differences (bias) among machines. Given the destructive nature of impact testing, and the lack of knowledge regarding the true breaking strength of the specimens, it is difficult to evaluate the absolute performance of Charpy impact machines. However, the relative performance of our machines can be examined. These types of horizontal comparisons help to define important similarities and differences between our impact machines and specimens, and the results allow us to target calibrations and changes to our respective programs that make them more transparent to the users.

Manuscript received December 21, 2004; accepted for publication October 21, 2005; published online January 2006. Presented at ASTM Symposium on Pendulum Impact Machines: Procedures and Specimens on 8 November 2004 in Washington, DC ; T. A. Siewert, M. P. Manahan, C. N. McCowan, and D. Vigliotti, Guest Editors.

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[7]Contribution of NIST; not subject to copyright.
[8]The National Research Laboratory of Metrology (NRLM) was reorganized as NMIJ.

TABLE 1—*Details of machines use for impact testing.*

Certification program	ID	Machine capacity (J)	Pendulum design	Dial/Encoder	Striker radius (mm)
	Machines				
		Details			
1	1	300	C	Dial	2
	2	300	C	Dial (until Oct 2003, then encoder)	2
2	3	350	U	Encoder	2
3	4	324	U	Encoder	8
	5	358	U	Encoder	8
	6	360	C	Encoder	8
4	7	500	C	Dial	2
	8	500	C	Dial	2

Materials and Procedures

Specimens

Verification specimens at three energy levels were used for testing. At each energy level samples came from a single batch. The specimens used for all of the verification specimens (low, medium, and high energy levels) were made using a heat treated AISI 4340 steel. The low energy specimens were heat treated to have a nominal energy of 15 J, when tested at −40°C. The medium energy specimens were heat treated to have a nominal energy of 30 J at 20°C. The high energy specimens were heat treated to have a certified energy near 100 J at −40°C.

Testing Details

The study was designed to test specimens twice a year over a three year period. On each test date, ten specimens at each of three energy levels were tested on each machine. Tests were performed at the temperatures for which the respective batches were produced (−40°C for low and high energy levels, 20°C for the medium energy level).

Machine Details

Eight pendulum impact machines were evaluated in this study, and some details concerning these machines are listed in Table 1. The grouping by *certification program* is of practical concern for this study, because there is interest in comparing the "verification systems" used in Europe, Japan, and the United States. The details for the machines and the average energy values determined for them in this study do not fully describe each of the certification systems [1]. In particular, Program 1 certifies Master Batches of impact specimens by use of an international intercomparison (with ten or more machines). To verify the performance of industrial pendulum impact machines, samples of so-called Secondary Batches are used. The Secondary specimens are compared with the Master specimens of the same nominal energy. These certification tests are done in repeatability conditions, on a single machine [2]. Until recently, this was machine 1, today this is done with machine 2. Therefore, a direct comparison of an impact machine from Program 1, with machines from Program 2, 3, or 4 is not a direct comparison of certification systems. Other details and interrelationships between machines and programs make direct comparisons difficult as well.

Fluctuations in the respective programs, due to machine repairs, part replacements, and other factors are expected to be apparent over the three-year period of this study. For example, the replacement of anvils might influence the energy value determined by a machine. So, correlations of machine performance with service records are considered.

Striker radii (2 and 8 mm) differ for the machines in this study. Although this is a real and identifiable variable for the machines, it is considered here as just another nonseparable machine variable or bias (2 and 8 mm results are directly compared). This approach is taken because the average differences in absorbed energy due to testing with 2 and 8 mm striker radii on these machines with AISI 4340 verification specimens is small considering the known magnitudes of machine bias [1]. The choice of striker was left up to the laboratory. The machines in program 1 and 2 always used a 2 mm striker radius, and the machines in program 3 always used an 8 mm striker radius. The machines in program 4 used the striker radii associated with the certified value of the specimens tested: 2 mm striker radii for medium energy level, and 8 mm striker radii for low and high energy specimens.

The maximum capacity of each machine is listed in Table 1. The capacities of machines 1 through 6 are similar, between 300 and 360 J. Machines 7 and 8 have the highest capacities used in the study, 500 J.

Results and Discussion

Specimen Stability

Before comparing relative machine performance, it is necessary to determine the stability of specimens over time. The seven tests performed in this study, over a three-year period (about every six months), allow a systematic investigation of the stability in time of the absorbed energy values of the batches. Since the data were collected at unequally spaced intervals, evaluations were based on actual measurement dates to obtain valid statistical tests as well as an accurate representation of the data over time. As shown in Fig. 1, a regression of the average energy for each machine and test date is made for each energy level, ignoring differences between machines. None of the regression slopes were significant at the 0.05 level.

A regression analysis of average energy versus test date was performed for each machine and energy level individually. Three slopes were found to be significant: The probability that the calculated slope would have occurred by chance if the "true" slope is zero for machine 3 at high energy was 0.002; For machine 6 at high energy the p value was 0.01; For machine 6 at low energy the p value was 0.03. The majority of machines do not display significant trends, and the trends noted are of magnitudes within the range of the overall (random) variation for several other machines. On average, the standard deviation of all the results on a single pendulum at a particular energy varies from 4 to 6 % (low energy), 5 to 7 % (medium energy), and 3 to 4 % (high energy)

We also analyzed the variance for each energy level based on machine and test date. The effect of the test date was not significant (at the 0.05 level) for any of the three energy levels even after accounting for differences between machines.

Conclusive evidence of specimen and machine stability is difficult to obtain. Because the Charpy test is destructive, it is difficult to separate drift in machines from drift in specimens with data obtained in this study. However, based on the results of the regression analyses using the combined data, it appears that the low, medium, and high energy level impact verification specimens were stable during the three-year period of the interlaboratory comparison. Assuming that specimens are stable, then there are two machines that may be drifting, machine numbers 3 and 6.

Further analyses were performed to determine whether the sample variance was stable across measurement occasions. Bartlett's test for equality of variance among measurement occasions was performed for each machine and energy level. Only one machine was found to have inhomogeneous variance across measurement occasions, machine 3 at high energy. This result indicates predictable behavior of machines over time with respect to variability, and is another indication of stability.

Estimates of Mean Energy

Table 2 displays means and standard deviations for each machine, test number, and energy level, as well as grand means and standard deviations based on the combined data. Considering the averages for each time point, as shown in Table 2, the differences between the grand mean and means of individual test numbers are small. The differences for low, medium, and high energy levels are within ±0.1 J, ±0.5 J, and ±1.8 J, respectively (less than 2 %). This variation in the estimates of mean energies for the specimens is small, but significant in context of the uncertainty that might be associated with certified values for verification specimens.

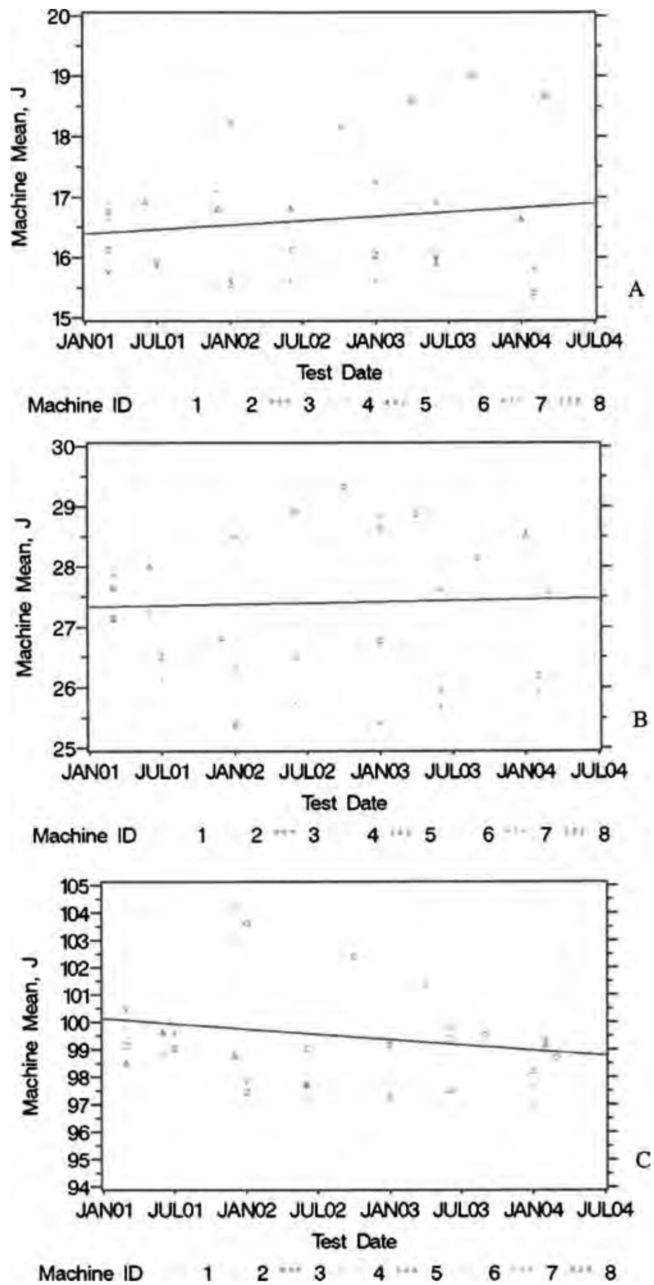

FIG. 1—*The (A) low* p=0.4, *(B) medium* p=0.8, *and (C) high energy* p=0.2 *plots and probabilities showing trends for specimen stability.*

Comparisons of Machines

If all machine means and variances were assumed to be stable we could combine measurement occasions and compare grand averages for each machines. However, machines may change over time, so we examined machines for each energy level and test number separately.

A one-way analysis of variance to determine the equality of machine averages was performed for each energy level and test number separately [2]. For all but two cases (test 2 at medium energy and test 1 at high energy) at least one machine was found to be statistically different from the other means at the 0.05 level of significance. Figure 2 shows energy means and associated variance bars for each machine and test number. The bars were computed as twice the standard deviation of the mean. Bars that overlap for any two machines indicate that the means for the machines are probably not significantly different. The figures represent a graphical confirmation of the analysis of variance results.

There is some evidence of a systematic offset between machines at low energy. Means for machines 6–8 are always lower than means observed for the other machines, while means for machines 2 and 3 are

TABLE 2—*Mean and standard deviation for individual tests and for combined (grand) values.*

Level	Test number	Mean energy (J)	Standard deviation (J)
H	1	100.3	1.3
H	2	99.3	3.0
H	3	100.8	3.1
H	4	99.4	2.3
H	5	99.0	1.4
H	6	99.1	1.6
H	7	99.0	1.9
H	Combined	99.5	2.1
M	1	27.9	0.7
M	2	26.9	0.7
M	3	26.7	1.0
M	4	27.9	1.5
M	5	27.7	1.3
M	6	27.0	1.1
M	7	27.5	1.0
M	Combined	27.5	1.1
L	1	16.5	0.7
L	2	16.5	0.6
L	3	16.5	1.1
L	4	16.7	1.2
L	5	16.7	1.3
L	6	16.7	1.2
L	7	16.7	1.4
L	Combined	16.6	1.0

typically higher than those observed for all other machines. Although there is some systematic difference among machines for medium energy (means for machines 6–8 are often lower than other machine means), there is no evidence of such an effect at high energy.

Another way to view the data is to plot energy means for each test number versus machine (Fig. 3). For low energy, the data indicate that means for each test number within a machine are fairly reproducible; however the separation of means among machines is quite large. For medium energy, the separation of means among machines is not quite as pronounced as for low energy. For high energy, means are fairly consistent among machines; however, the means for each test number within a machine are generally less repeatable.

Interlaboratory Comparisons

The evaluation of interlaboratory comparison data has been considered at length by international measurement laboratories, and working groups have been tasked with providing guidelines for these types of analyses. We can apply interlaboratory principles to the current data by assuming machines are laboratories. For example, Cox proposed an interlaboratory comparison procedure (Procedure A) for which nearly all the assumptions are satisfied [3]. The one assumption that may be violated specifies that measurements from all machines are independent (there may be some correlation among machines within a single laboratory). With this caveat in mind, we apply Procedure A to single test numbers and energy levels to provide a better reference for comparisons. The procedure used is as follows:

1. Determine the mean of all machines.
2. Determine the standard deviation of the mean.
3. Apply a chi-squared test to evaluate the overall consistency of the results.
4. If the consistency check does *not fail*, then we accept the mean as the reference value and calculate degrees of equivalence (or machine biases in our case).
5. If the consistency check *fails*, then an investigation would be implemented to resolve the inconsistencies.

Cox does not recommend computing a reference value unless the laboratories, or machines in our case, are consistent. For our machine comparison, only data from the test number one at high energy passed the

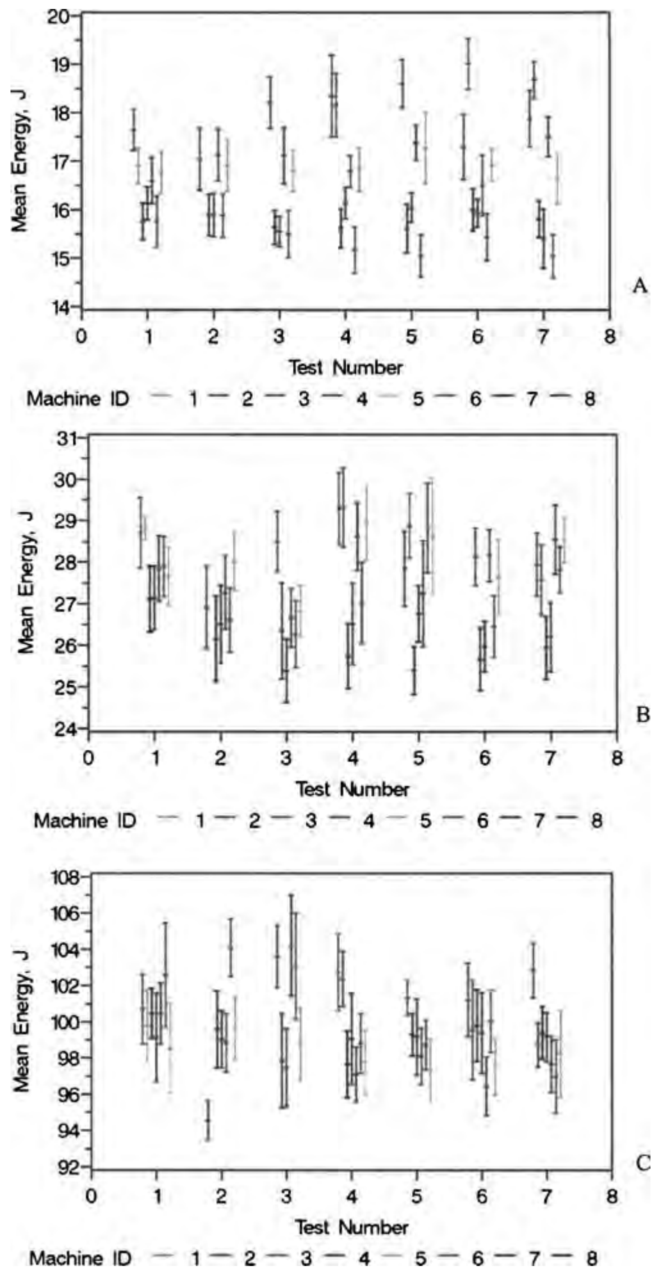

FIG. 2—*The average energy for each machine versus test number for: (A) low energy, (B) medium energy, and (C) high energy. Error bars are twice the standard deviation of the mean.*

consistency check, confirming the analysis of variance results discussed earlier. In general, the results of applying Procedure A indicate that more work is needed to develop and maintain a measurement of impact energy that is internationally consistent.

Contributions to Machine Bias

There are some recognized factors that might be expected to contribute to the bias between machines that are all in full compliance with direct verification requirements. These factors include striker radius, machine capacity, and pendulum design.

There have been numerous studies showing effect of 2 mm versus 8 mm striker radius designs on the measured energy of an impact test. [4–8] Clearly the effect of striker geometry is material dependent, and here only the effects relative to specimens made from type 4340 steel need to be considered. In this study the effect of striker geometry cannot be separated from other machine variables, but we can use data from a previous comparison for this purpose, and these data, shown in Fig. 4, include results for four of the machines used in this current comparison [1].

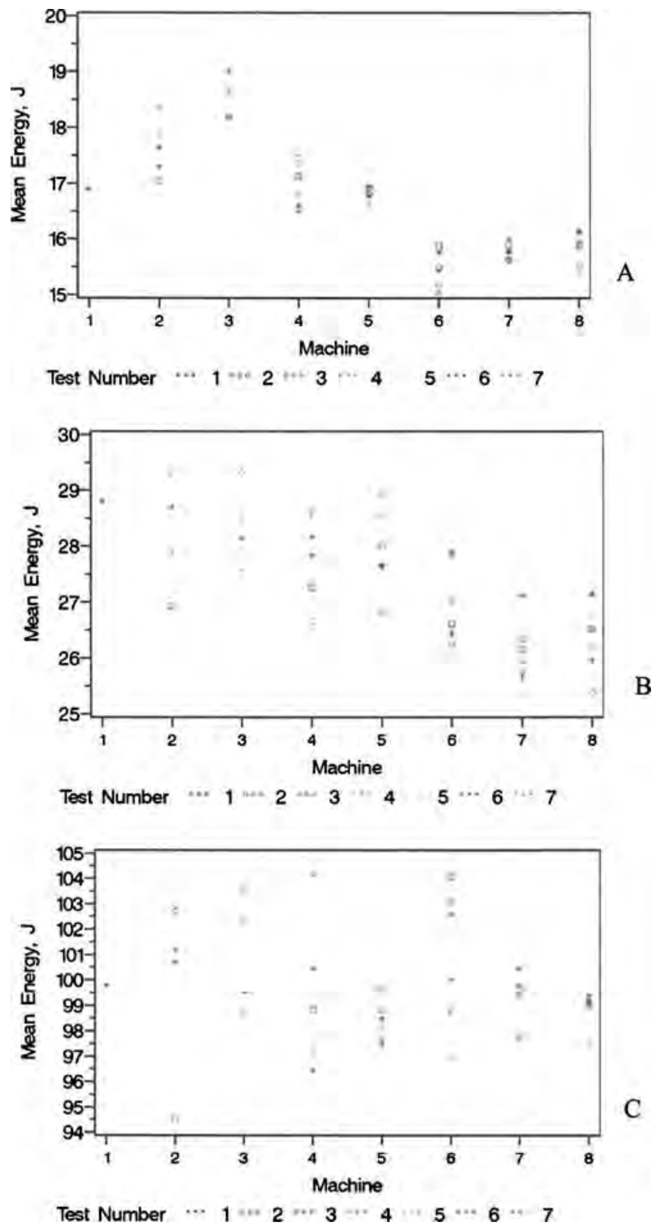

FIG. 3—*The average energy of (a) low, (b) medium, and (c) high energy specimens is shown for each machine and test. Here the grouping of data for a given machine is most apparent. At low energy (a) the relative difference between machines and the lack of overlap for the data indicated clear differences due to the machines.*

The data were generated by testing 15 specimens with a 2 mm striker and ten specimens with an 8 mm striker on each machine for nine sets of specimens (between 15 and 120 J). The average percent differences between the 8 and 2 mm radius strikers for these data at the nominal energy levels of 16, 25, 70, and 100 J are, respectively, about −3 % (−0.44 J), −0.2 % (−0.06 J), −1 % (−0.7 J), and −1 % (−0.9 J). Details in Fig. 4(*b*) show the average values for specimens of very low energy are strongly influenced by individual machines (or tests), so the average difference of −3 % at 16 J may be somewhat misleading. This is supported by the three sets of data near 25 J, for which no significant effect is shown. At 60 J and above, however, there is a trend that is reflected well by the average values. The machines tend to get higher energy results from a striker with a 2 mm radius, compared with results for 8 mm strikers. The magnitude of this effect (average of −1 %) is reasonably convincing because it is independent of the impact machine used for the test and on the origin of the specimens tested. Overall, a magnitude of 1 to 2 % seems like a reasonable approximation for the magnitude of the contribution of striker geometry to the machine bias in this study, and at low energies the effect may be much smaller. This last point is in

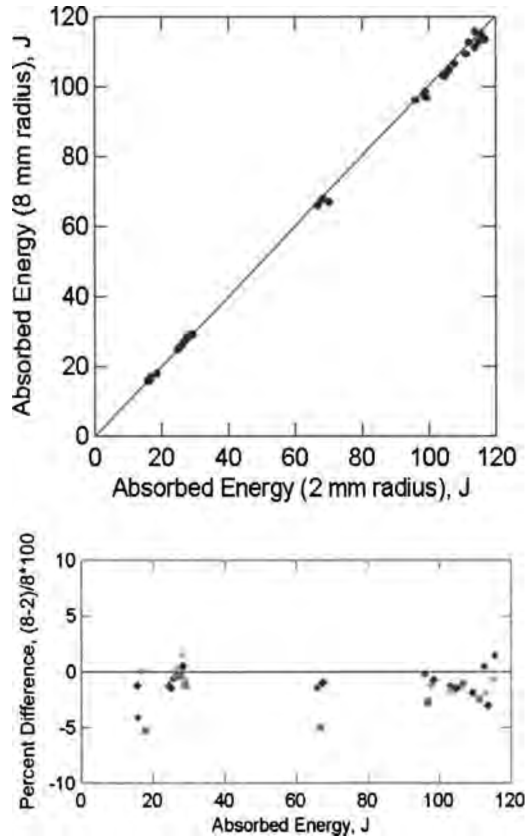

FIG. 4—*A comparison of data for 8 and 2 mm striker geometries gathered by use of reference impact pendulums and type 4340 verification specimens. The upper plot (a) shows a general comparison, and the lower plot (b) shows the percent difference of the 8 and 2 mm striker data gathered on each machine (colors), for each set of verification specimens tested (the 2 mm data was subtracted from the 8 mm data, divided by the 8 mm data, and multiplied by 100).*

agreement with the speculation that strikers with a smaller radius penetrate deeper into softer materials (hardness of 4340 steel specimens decreases as energy increases), which absorbs energy and results in higher measured impact energy [5].

The small effect of striker geometry does not help to explain the differences in machines observed at low energy, where machine differences were largest and best defined. However, it can be argued that at the high energy level, the effect of striker geometry should increase the energy measured by the machines with the 2 mm strikers by about 1 % compared with the machines using 8 mm strikers (machines 4, 5, and 6). There is not a clear trend for this argument, since consistent differences between machines at the high energy level due to striker radii are not apparent for the data taken in this comparison. For example, machines 6, 7, and 8 [Fig. 3(*c*)] have very similar designs, and the results for machine 6 (8 mm striker) are often higher than the results for machines 7 and 8 (2 mm strikers). Also, the differences between machines are too large in many cases to be attributed solely to striker geometry alone, and are likely confounded by other variables.

Machine capacity is not expected to be a significant variable here. The range in capacities for the machines is approximately 300 to 500 J and this range is too small to investigate the influence of capacity. Both of the 500 J machines (machines 7 and 8) tend to perform in a very similar manner, but this is due to overall machine design rather than capacity. We base this on the fact that machine 6 has very similar design and performance to machines 7 and 8, but it has a different capacity (360 J).

The pendulum design, C-type or U-type, alone cannot be identified as contributing to lower or higher energy values. Machines 6–8, which are C-type designs, often performed conservatively compared with the other machines. But machines 1 and 2, which are also C-type designs, often produced energy values higher than the grand mean values.

Machine Maintenance Effects

During the three-year period the participating machines underwent regular (typically annual) direct verifications. At such occasions, deviations from desired machine parameters can lead to replacement or adjustment of particular parts of the pendulum. Such actions can also be purely preventive. An overview of the major maintenance actions (mainly replacement of anvils, supports, or striker) failed to reveal a correlation with the measured values.

Summary and Closing Remarks

Currently, the verification programs associated with IRMM, LNE, NIST, and NMIJ all have machines that are performing within expected and reasonable bounds, and each program can consistently assign certified energies that are stable and suitable relative to their respective user groups. However, the bias between machines makes it difficult for the laboratories to independently provide measures of impact energy for the international community. Providing an internationally defined target for impact energy will require further cooperation between the laboratories and the implementation of a robust and traceable certification process.

Conclusions

The average energies measured for the three levels of impact verification specimens were stable over the three year duration of the study. This indicates that reasonable shelf life can be expected for properly heat treated type 4340 steel impact verification specimens.

Overall, the machines, and groupings of machines by program, appear to be stable over the three-year test period.

The grand average over all machines at each of the three energy levels seems sufficiently stable for the production and maintenance of an international reference value. However, the consistent differences between machines are larger than desirable for this "International Master Batch" approach.

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Journal of ASTM International, July/August 2005, Vol. 2, No. 7
Paper ID JAI12870
Available online at www.astm.org

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Certification of Charpy V-Notch Reference Test Pieces at IRMM

ABSTRACT: The Institute for Reference Materials and Measurements (IRMM) of the Joint Research Centre (JRC) of the European Commission (EC) is one of the reference materials producers which certifies reference test pieces for the indirect verification of Charpy pendulum impact machines. The certification approach taken at IRMM consists of two main steps. In a first step, a Master Batch of reference test pieces is certified for each of a number of chosen nominal energy levels (currently 30 J, 60 J, 80 J, 120 J, and 160 J). The certified absorbed energy value of these Master Batches is determined in an international round-robin. In the second step of the certification process, the Master Batch test pieces are used to determine the certified value of Secondary Batches of reference test pieces of the same nominal energy. This is achieved by comparing samples of Master and Secondary Batch under repeatability conditions. In this paper, this Master Batch – Secondary Batch approach is critically assessed in terms of traceability and uncertainty of the certified absorbed energy. It is shown that the produced reference test pieces are fit-for-purpose: they meet the requirements of their intended use (indirect verification).

KEYWORDS: Charpy V-notch certified reference test pieces, certified reference material, absorbed energy, traceability, uncertainty

Introduction

The energy absorbed by a steel test piece of well-defined Charpy V-notch geometry during pendulum impact fracture depends on the pendulum construction and dynamic behavior. European, American, and ISO standards [1–3] describe methods to verify the performance of an impact pendulum, distinguishing direct and indirect verification. Indirect verification consists of breaking a set of five reference test pieces. For a pendulum to pass the indirect verification, the absorbed energy (KV, unit: Joule) values measured for the five test pieces need to meet criteria of accuracy (average within certain limits of the certified value) and repeatability (difference between smallest and largest KV smaller than a certain percentage of the certified KV).

Reference test pieces for the indirect verification of Charpy impact pendulum test machines can be obtained from a number of Certified Reference Material (CRM) producers, one of which is the Institute for Reference Materials and Measurements (IRMM) of the Joint Research Centre (JRC) of the European Commission (EC) in Geel, Belgium. About five years ago, IRMM took over the reference material certification activities formerly managed by the EC Community Bureau of Reference (BCR). The Charpy V-notch certified reference test pieces referred to in EN and ISO standards as 'BCR test pieces' [1,4] are now available as ERM-materials. ERM is the trademark of certified reference materials produced by the European Reference Materials

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Manuscript received 5 November 2004; accepted for publication 10 January 2005; published July 2005. Presented at ASTM Symposium on Pendulum Impact Machines: Procedures and Specimens on 8 November 2004 in Washington, DC.
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consortium [currently consisting of the founding members IRMM (EC), BAM (Germany), and LGC (United Kingdom)].

The transfer of the Charpy reference test pieces from former BCR to current ERM status has been accompanied by a critical evaluation of the certification procedure. No major changes have occurred, and the certification of Charpy V-notch reference test pieces still is performed largely in accordance with the procedures described in the BCR-reports by Marchandise et al. [5] and Varma [6]. This paper provides the reader with an up-to-date description and critical assessment of the certification procedure as it is applied today at IRMM.

The Concept of Master Batch and Secondary Batch: Implications for Traceability and Uncertainty of the Certified Absorbed Energy Values

Intended Use – Fit-for-Purpose CRMs

The production of CRMs at IRMM is approached with the 'fit-for-purpose' concept in mind. The purpose to be served by the Charpy V-notch reference test pieces is the indirect verification of industrial and reference impact pendulums. Indirect verification consists of breaking five reference test pieces and must be performed at least at two different energy levels covering as large a part of the pendulum energy range as possible. The indirect verification is recommended (EN 10045-2 [1]) or required (ISO 148-2 [3]) to be performed at least annually. Given the destructive character of the test, reference test pieces can only be used once. With an estimated number of several thousand Charpy pendulums worldwide, the production method of the reference test pieces must be adequate for application at a large scale. While mass-production is required on one hand, the uncertainty of the certified absorbed energy must be sufficiently small. The maximum allowed uncertainty must be seen in connection with the indirect verification criteria imposed in the standards. ISO and EN standards require the owner of a pendulum to prove that the average absorbed energy of five reference test pieces from a single set on his pendulum is within 10 % (industrial pendulum) or 5 % (reference pendulum) of the certified absorbed energy. Therefore, this certified value and the associated uncertainty must pertain to the average of a set of five reference test pieces, as distributed to the customer. With current verification criteria, the uncertainty at a confidence level of 95 % must minimally be less than 10 %, but preferably also sufficiently less than 5 % to also serve the reference pendulum owners. The following paragraphs explain how the so-called Master Batch - Secondary Batch concept enables IRMM to produce large numbers of test pieces with a sufficiently small uncertainty of the certified value.

Traceability and Uncertainty of the Certified Absorbed Energy of Master Batch Test Pieces

The first production of Charpy Master Batches is described in BCR reports [5] and [6]. Recently, IRMM has launched the production of new Master Batches. Until completion of the newly started certification, the Master Batches presented in [5] and [6] will continue to be used at IRMM. The certified values of these Master Batches were determined through an international laboratory intercomparison, each lab testing in accordance with the method described in EN 10045-1 [7] and ISO 148 [8]. While initially certified values were obtained both for 2 and for 8 mm tip radius strikers, only the results obtained using strikers with 2 mm radius at the tip - normative in the EN standard - are considered by IRMM today. Participants to the intercomparison were selected based on the performance of their pendulum(s), as assessed with the direct machine verification criteria imposed in EN and ISO standards, and through a preliminary intercomparison. The certified value is calculated as the mean of all technically accepted laboratory mean values. With respect to traceability, this means that the certified absorbed energy values of the Master Batches are method-specific values, expressed in Joules, obtained according to the Charpy impact test described in EN 10045-1 and ISO 148.

The standard uncertainty associated with the certified value of the Master Batch is determined as the standard deviation of the laboratory mean values, divided by the square root of the number of accepted data sets. Basically, one assumes that the participating instruments are a representative sample of all pendulum designs that meet the normative standards, and that all allowed differences between pendulums result in a normal distribution of KV values. The validity of the latter assumption might have to be reconsidered. It is possible that different machine designs, while meeting the specifications of the standards, consistently give (slightly) different average KV values. Such difference is difficult to observe, as the scatter in KV values is dominated by sample-to-sample heterogeneity. Large-scale testing campaigns such as the International Master Batch project [9] are required to tackle this issue. If the normal distribution will not be confirmed, then one would have to use a different statistical approach to account for a larger uncertainty to the Master Batch certified absorbed energy value. This consideration will be made when certifying the new ERM Master Batches.

Traceability and Uncertainty of the Certified Value of a Secondary Batch of Test Pieces

The certification of the Secondary Batch is based on the comparison of a set of Secondary Batch test pieces with a set of test pieces from the corresponding Master Batch (i.e., the Master Batch with the same nominal energy) on a single impact pendulum under repeatability conditions. With this approach one avoids frequent repetition of the time-consuming and costly international intercomparison, and this enables a more cost-efficient production of large numbers of certified reference test pieces. The traceability of the certified value remains assured and is expressed as follows: the certified absorbed energy of a Secondary Batch is a method-specific value, traceable, via the corresponding Master Batch, to the Charpy impact test as described in EN 10045-1 and ISO 148.

The reports by Marchandise et al. [5] and Varma [6] were published in 1991 and 1999, respectively. Since 2000, the calculation of the certified value of the Secondary Batch test pieces and the estimation of the associated uncertainties has been updated to an approach compliant with the ISO Guide to the Expression of Uncertainty in Measurement [10]. This revised approach was developed and presented by Ingelbrecht et al. [11,12] and is summarized here.

The certified mean absorbed energy of a Secondary Batch of Charpy V-notch reference test pieces (KV_{SB}) is calculated from the certified value of the Master Batch (KV_{MB}) and from the mean values (X_{SB} and X_{MB}) of the sets of measurements carried out under repeatability conditions on Secondary and on Master Batch samples, respectively. Basically, to obtain KV_{SB} one corrects X_{SB} by the ratio of the Master Batch values, as follows:

$$KV_{SB} = \left[\frac{KV_{MB}}{X_{MB}} \cdot X_{SB} \right] \qquad (1)$$

The standard uncertainty u_{SB} of KV_{SB} is obtained from Eq 2, which sums the relative uncertainties of the three factors in Eq 1:

$$\frac{u_{SB}^2}{KV_{SB}^2} = \frac{{s_p}^2}{p \cdot KV_{MB}^2} + \frac{s_{SB}^2}{n_{SB} X_{SB}^2} + \frac{s_{MB}^2}{n_{MB} X_{MB}^2} \tag{2}$$

where p is the number of accepted sets of results from the interlaboratory characterization of the Master Batch; s_p is the standard deviation of laboratory means obtained in the certification of the Master Batch; s_{SB} is the standard deviation of results for the Secondary Batch (n_{SB} specimens) obtained in the comparison with the Master Batch; and s_{MB} is the standard deviation of the results for the Master Batch (n_{MB} specimens) in the certification of the Secondary Batch.

Equation 2 shows that the uncertainty of the certified value of the Secondary Batch is affected by the heterogeneity of both the Master Batch and the Secondary Batch. The heterogeneity of the Master Batch contributes to the uncertainty on the certified value of the Master Batch, as to some extent it increases the standard deviation s_p of the mean values of the laboratories, which participated in the characterization of the Master Batch. The Master Batch heterogeneity also affects the uncertainty of the mean KV value of the Master Batch samples on the pendulum used for the characterization of the Secondary Batch through s_{MB}, the standard deviation of these measurements. Similarly, the Secondary Batch heterogeneity affects the uncertainty u_{SB} through s_{SB}, the standard deviation of the results obtained on the samples of the Secondary Batch.

Certified Value and Associated Uncertainty of a Set of Five Test Pieces from a Secondary Batch

The expected mean value of the actual Certified Reference Material, i.e., a set of five test pieces from a Secondary Batch, is equal to the certified value of the Secondary Batch. Therefore, the certified absorbed energy of the set of Charpy reference test pieces, KV_{CRM}, is equal to KV_{SB}. However, the uncertainty u_{CRM}, associated with KV_{CRM}, is larger than u_{SB}. The additional uncertainty contribution is due to the fact that the set of five test pieces is sampled from the Secondary Batch, which is not perfectly homogeneous. The corresponding uncertainty is estimated from the standard deviation of the results of the characterization tests on the Secondary Batch, as $\frac{s_{SB}^2}{5}$. Adding this uncertainty contribution to Eq 2, and using the approximation $KV_{SB} \approx KV_{MB} \approx X_{SB} \approx X_{MB}$, the certified value KV_{CRM} and corresponding expanded uncertainty U_{CRM} can be obtained as:

$$KV_{CRM} \pm U_{CRM} = KV_{SB} \pm k \cdot u_{CRM} = KV_{SB} \pm k \cdot \left[\frac{{s_p}^2}{p} + \frac{s_{MB}^2}{n_{MB}} + \frac{s_{SB}^2}{n_{SB}} + \frac{s_{SB}^2}{5} \right]^{1/2} \tag{3}$$

The relevant number of degrees of freedom ν_{eff} can be calculated using the Welch-Satterthwaite equation, but as in this case ν_{eff} >>10, a coverage factor k = 2 is adopted to obtain an expanded uncertainty with confidence level of 95 %.

Processing of ERM Charpy V-Notch Certified Reference Test Pieces

The processing of ERM Master and Secondary Batches is carried out at IRMM subcontractors. The certified reference test pieces of nominal energies 30 J, 60 J, 80 J, and 120 J are made from hot-rolled bars of AISI-SAE 4340 NiCrMo steel. The 160 J nominal energy batches are produced from bars of ASTM 565 grade XM-32 martensitic stainless steel. The compositional tolerance of the selected steel batches is stricter than generally allowed, to limit the amount of impurities potentially affecting the homogeneity of the impact resistance.

Target absorbed energies are achieved by choosing the appropriate heat treatment to create the desired microstructure. Details of the heat treatment procedure are different between subcontractors. The former subcontractor performed the heat treatments after cutting the hot rolled bars into rectangular beams of 58 mm length. At the current subcontractor, the hot-rolled bars are heat-treated at full length. In each case, the austenization step is followed by a quench and an annealing step. After heat treatment, the samples are machined to the test piece dimensions imposed in EN 10045-2 [1] and ISO 148-3 [4]. Ultimately, samples are cleaned and packed in sets of five in oil-filled plastic bags. These oil-filled bags, together with a label, again are packed in a sealed plastic bag and shipped to IRMM, where they are stored at 18°C until they are sold.

Certification of a Secondary Batch of ERM Charpy V-Notch Reference Test Pieces

The following paragraphs will illustrate the calculation of certified value and uncertainty of a set of five reference test pieces, using the results obtained on the Secondary Batch ERM-FA014n, which was compared with Master Batch ERM-FA014c (both batches have a nominal absorbed energy of 60 J).

Characterization Tests and Homogeneity

The characterization of Secondary Batches, by comparison with the corresponding Master Batch, has to be performed under repeatability conditions. The Secondary Batch ERM-FA014n was compared with Master Batch ERM-FA014c on the Metro Com 2005 machine of Cogne Acciai Speciali (Italy). Charpy impact tests were performed according to EN 10045-1 [7]. The results of these measurements and the resulting certified value and associated uncertainty are summarized below in Table 1. The relative standard deviation (RSD) of the Secondary Batch clearly meets the EN-10045-2 and ISO-148-3 acceptance criteria (RSD < 5 %).

As was done for the ERM-FA014n batch, certification tests on Secondary Batches used to be subcontracted by IRMM. However, in 2000, an Instron-Wolpert PW30 pendulum (300 J, C-type hammer) was installed at IRMM. After the required period of training and indirect and direct verifications, the IRMM laboratory now has acquired the expertise to characterize the Secondary Batches in-house under repeatability conditions. The aid and advice from the other partners in the International Master Batch project [9] must be acknowledged.

The Stability Issue

The stability of the absorbed energy of Charpy V-notch certified reference test pieces has been systematically investigated for samples of nominally 120 J by Pauwels et al. [13]. In these tests no measurable changes of absorbed energy were observed [13]. The main reason for the microstructural stability of the certified reference test pieces is the annealing treatment to which the samples are subjected after the austenization treatment. Annealing is performed at temperatures where the equilibrium phases are the same as the (meta-)stable phases at ambient temperature (α-Fe and Fe_3C). A potential driving force for instability stems from the difference in solubility of interstitial elements in the α-Fe matrix, between annealing and ambient temperature. Relaxation of residual (micro-)stress by short-range diffusion or the additional formation or growth of precipitates during the shelf-life of the certified reference test pieces is expected to proceed but slowly. Given the large sample-to-sample heterogeneity, the aging effects are too small to be detected when testing limited numbers of samples, and the uncertainty contribution from instability has been considered to be insignificant. The most recent information on the long-term stability of Charpy reference test pieces can be found in the report on the International Master Batch project [9].

Calculation of Certified Absorbed Energy and Associated Uncertainty

Table 1 presents all data involved in the calculation of KV_{CRM}, the certified value of a set of five reference test pieces, for the Secondary Batch ERM-FA014n. The certified values KV_{CRM} and U_{CRM} are obtained directly from Eqs 1 and 3.

TABLE 1—*Input data and results of calculation of certified absorbed energy value and uncertainty of a set of five reference test pieces of batch ERM-FA014n.*

	ERM-FA014c (MB)		ERM-FA014n (SB)	
Results of SB-characterization	n_{MB} (-)	25	n_{SB} (-)	30
	X_{MB} (J)	54.78	X_{SB} (J)	58.63
	s_{MB} (J)	1.04	s_{SB} (J)	1.48
	s_{MB}/X_{MB} (%)	1.9	s_{SB}/X_{SB} (%)	2.5
Certified Values	KV_{MB} (J)	56.8	KV_{CRM} (J)	60.7
	u_{MB} (J) (standard uncertainty, k = 1, 67 % confidence range)	0.4	U_{CRM} (J) (expanded uncertainty, k = 2, 95 % confidence range)	1.7
			Relative U_{CRM} (%) (expanded uncertainty, k = 2, 95 % confidence range)	2.8

Discussion

Fitness of the Certified Reference Test Pieces for Indirect Verification

Until full agreement is reached at the international level about appropriate ways to handle uncertainty in Charpy tests, the indirect verification will exclusively govern the mutual acceptance of Charpy test results between steel producers and users. The results shown in Table 1 indicate that the production of the ERM-FA014n batch of reference test pieces through the Master Batch – Secondary Batch approach leads to an uncertainty of the certified absorbed energy that meets the requirements for the intended use of indirect verification. The average uncertainty of the certified value for sets of five reference test pieces from all batches produced at IRMM in the last seven years, is equal to 3.0 % (expanded uncertainty U_{CRM}, coverage factor k = 2, corresponding with a 95 % confidence level).

Issues to be Tackled When Narrowing the Indirect Verification Limits

It is currently being investigated whether the indirect verification criteria specified in ISO 148-2 [3] (10 % deviation from the certified energy for the average KV of a set of five reference test pieces on an industrial pendulum) can be reduced to 5 % to reach a status of equivalence with the more strict ASTM E 28 [2]. At this point, it is important to come back to two remarks made earlier in this paper.

A first issue that needs to be tackled prior to reducing the indirect verification criteria is the estimate of the uncertainty of the Master Batch certified absorbed energy. The current standards allow for a number of pendulum designs to exist and specify a number of features with tolerances that vary more or less widely. These different pendulum designs (such as the difference between C- and U-type hammers, the maximum energy of the pendulum, the 2 and 8 mm strikers) could produce a bias, so this effect should be studied. If consistent differences are observed, then these must be acknowledged. This would imply that the indirect verification criterion allows for a sufficiently broad acceptance range, or, alternatively, that the uncertainty of the certified reference test pieces accounts for the non-normally distributed variation between pendulums.

The second issue is that of stability. While more and more evidence points toward a satisfactory stability of the absorbed energy of the certified reference test pieces [9], so far there has been no sufficiently detailed investigation to produce a reliable quantitative estimate of the stability-contribution to the overall uncertainty. One way of limiting the uncertainty contribution from material (in)stability is defining a shelf-life. This would require a more regular repetition of the intercomparison exercise. Possibly, an agreement can be reached to constitute a worldwide permanent network of reference pendulums regularly producing an International Master Batch. This network should be dynamic and reliable, i.e., open to all reference pendulums, which perform with satisfactory stability over a period of, for example, five years prior to joining the network. Throughout the existence of the network, pendulums would automatically be cross-monitored, thus allowing detection and closer investigation of drifts or sudden changes in mean values.

How to Further Reduce the Uncertainty Associated with the Certified KV of Reference Test Pieces

Once solved, the two issues above will provide us with an even more reliable and possibly – depending on the decision on how to account for allowed variations between machines – a larger uncertainty estimate for the certified KV of the reference test pieces. If the latter is the case, and if the desire to impose more stringent indirect verification criteria is moved forward, then it is important to investigate whether the production of the certified reference test pieces can be changed to provide smaller uncertainties to the certified absorbed energy. FIG. 1 presents an overview of the relative importance of the different contributions to uncertainty as identified in Eq 3. The numbers are obtained by averaging the uncertainty contributions over all batches produced at IRMM in the last seven years. It is obvious from Fig. 1 that the major contribution to uncertainty is the one due to the fact that the user receives a set of five test pieces sampled from a large and relatively heterogeneous batch ($\frac{s_{SB}^2}{5}$). This ‘sampling’ contribution to uncertainty can be made smaller by increasing the homogeneity of the Secondary Batch. However, taking into account the considerable efforts already spent today in achieving the current level of homogeneity, this does not seem to be an option. An alternative solution is increasing the number of samples tested during indirect verification. This might be an option, especially for reference pendulums which today already need to meet the 5 % accuracy criterion. However, cost for the pendulum owner purchasing more certified reference test pieces would increase at a much faster rate than the reduction of uncertainty: testing ten samples (cost × 2) only reduces the uncertainty of the certified absorbed energy as calculated in Eq 3 from 3.0 % to 2.5 % (uncertainty × 0.83).

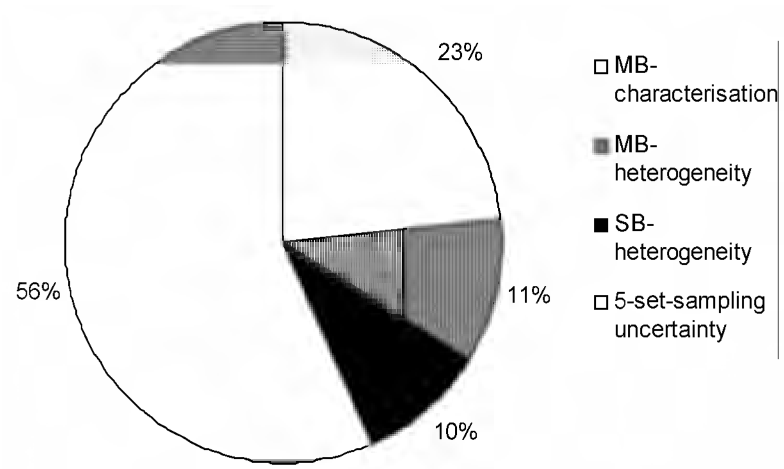

FIG. 1—*Relative importance of the contributions to the uncertainty of the certified absorbed energy of a set of five reference test pieces from a Secondary Batch (values are averaged over all Secondary Batches certified at IRMM between 1999 and 2004).*

The Uncertainty Budget of Charpy Impact Tests

In the discussion in the previous paragraph, the uncertainty estimate as provided by IRMM on the CRM certificates has shown its value in judging current and possible future indirect verification criteria. A few documents [14–17] indicate that the uncertainty associated with the certified value of the reference test pieces also needs to be considered as a substantial contribution to the uncertainty of the measurements made on a particular indirectly verified pendulum. However, the individual users of Charpy pendulums have not yet been encouraged to make effective use of the uncertainty provided on the CRM certificates as provided by IRMM. Currently, initiatives are taken at ISO level to provide informative annexes to the ISO 148-series of Charpy standards. These documents should provide a consistent approach to the uncertainty question, addressing not only the uncertainty of the certified KV of the reference test pieces, as is done in this paper, but also the uncertainty of the results of a (series of) test(s) on non-reference test pieces and the uncertainty budget associated with the verification of a pendulum.

Conclusions

This paper has shown in detail how IRMM certifies Charpy V-notch reference test pieces for the indirect verification of Charpy impact pendulums. Starting from a description of the intended use, the Master Batch – Secondary Batch approach to Charpy reference test piece certification is presented and shown to provide fit-for-purpose reference test pieces. The traceability of the certified absorbed energy of Master and Secondary Batches is defined. The uncertainty of the certified value for a set of five reference test pieces from a Secondary Batch is calculated (average value 3.0 %). The paper concludes with a discussion of the relevance of the uncertainty estimate of the certified absorbed energy for reference test pieces when deciding on changes in the indirect verification criteria.

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Journal of ASTM International, October 2005, Vol. 2, No. 9
Paper ID JAI12871
Available online at www.astm.org

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Uncertainty Analyses on Reference Values of Charpy Impact Test Specimens

ABSTRACT: The uncertainties of reference values of specimens, which are used for the verification of the secondary standard Charpy impact test machine, are investigated. To evaluate the uncertainty of the reference values of specimens, the results of the direct verification of the machine and the repeatability of measurement are considered. The uncertainty components estimated from the direct verification are calculated multiplying the uncertainty of each item and corresponding sensitivity coefficient. The repeatability of measurement is estimated from the results of the routine check data of the standard machine. By combining these components, the overall uncertainties of reference specimens are presented at 30, 100, and 160 J levels of absorbed energy.

KEYWORDS: Charpy impact test, direct verification, indirect verification, reference value, measurement uncertainty

Introduction

Recently, the *traceability* of measurement is required for the mutual recognition of the measurement standard, the accreditation of calibration or testing laboratories, etc. In the ISO standards for various fields, the procedures to estimate uncertainties have been developed and described in a part of standard. For the Charpy impact test, some laboratories have investigated the method to evaluate the uncertainty [1,2], and the discussion to develop the standard procedure for ISO has been started in the technical committee for the pendulum impact test (ISO/TC164/SC4P). At the same time, the effort to establish the international reference values has been made, and the international comparison were carried out between national-level laboratories in the world. However, remarkable differences between reference machines are found, and the differences exceed the repeatability of each reference machine [3]. For understanding this situation, it is necessary to develop a reasonable method to estimate uncertainty.

In this study, a method to estimate uncertainty according to the direct and indirect verification data of reference machines is proposed, and the validity of the uncertainty budgets are investigated.

There could be two different ways to estimate overall uncertainty of impact test, i.e., so called "top-down" and "bottom-up" approaches. The top-down approach is the procedure in which the uncertainty is estimated from the data of several reference machines to include their repeatability, stability, and also the differences among the reference machines. On the other hand, in the bottom-up approach, the uncertainty is estimated by combining the contributions of various sources in the measurement of impact values. Every reference machine must be verified

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Manuscript received 23 November 2004; accepted for publication 23 February 2005; published October 2005.
Presented at ASTM Symposium on Pendulum Impact Machines: Procedures and Specimens on 8 November 2004 in Washington, DC.
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in the direct and indirect methods as required in ISO 148-2 [4] and 148-3 [5]. The results of the direct verification include the information of machine condition, and if this information is combined together, the uncertainty components specific for the machine can be estimated. The overall uncertainty will be obtained by combining this component and the repeatability evaluated through the indirect verification, and the estimated overall uncertainty is expected to agree with the value estimated in the top-down approach.

Certification Program in Japan

National Standard Charpy Machines

The national standard of Charpy impact testing is established, maintained, and disseminated by the National Metrology Institute of Japan (NMIJ), and the certified values of specimens are determined by three 500 J machines (Fig. 1). The machines manufactured by Tokyokoki Seizousho Ltd. are equipped with a C-type pendulum, and its frames were specially designed as standard machines so that they are stiffer than any industrial machines. Both 2-mm and 8-mm strikers can be installed according to the purpose of testing. The angle of the pendulum is read with dial indicators. The machines are verified once a year in the direct method according to ISO 148-3, and the condition of each machine is verified with specimens which are picked from the same batch used in the previous year. The latter procedure is the substitution for the indirect method of ISO 148-3. Three machines are verified at the same time, and any change of machine conditions can be detected to compare the performance of three machines to each other.

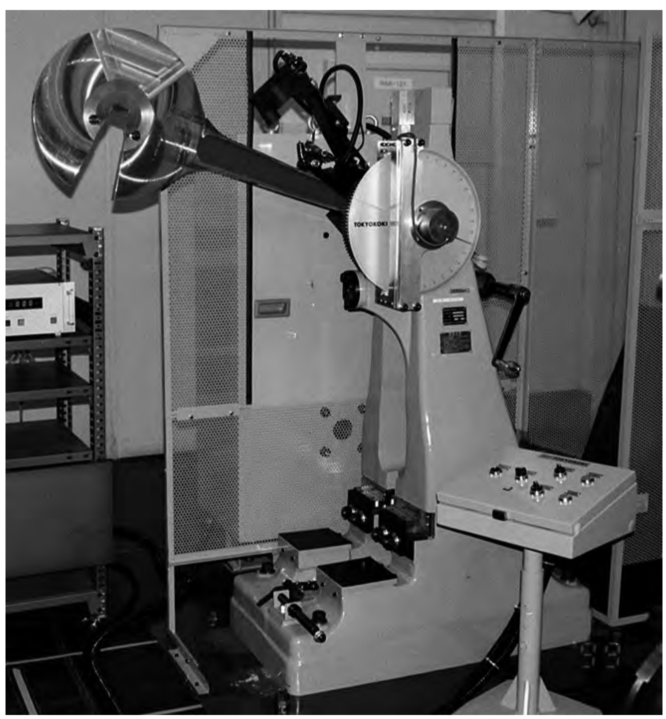

FIG. 1—*500 J national standard machine.*

Dissemination of Charpy Standard

NMIJ provides the testing service which verifies a Charpy machine of a calibration laboratory, which provides the traceable verification for industries. At the present stage, only one calibration laboratory, i.e., Nippon Kaiji Kyokai (ClassNK), verifies approximately 600 Charpy machines annually. NMIJ carries out the direct and indirect verification for the calibration laboratory and for this purpose, NMIJ prepares the certified specimens of 30, 100, and 160 J levels as transfer standards. Twenty-five specimens of a certified batch are used for the indirect verification of each machine. The temperature of the test is usually 0ºC, and the 2-mm striker is used.

Manufacture of the Reference Specimens

The specimens are supplied by two private companies, Asahi Giken Co. Ltd. and Yamamoto Scientific Tool Laboratory Co. Ltd (YSTL). They manufacture specimens in small batches, and the minimum size of the batch is 100. Although the material is supplied in large amount, the homogeneity of material is not acceptable all over the batch. YSTL treats a batch of material as a group of small parts, and they obtain 100 specimens from each part. Homogeneity in a part is typically 3 %, and it is better than that of whole material [6]. NMIJ uses 25 specimens to certify each batch with the standard impact machine.

Method to Estimate the Uncertainty

Outline of the Uncertainty of Reference Specimens of Charpy Impact Test

Values directly measured in Charpy impact tests are

α Fall angle,

β Rise angle,

l Distance between the center of percussion and the axis of rotation,

F Force exerted by the pendulum on the force-proving device for distance l ,

and an absorbed energy is calculated with following equation:

$$K = f(\alpha,\beta,l,F) = F \cdot l \cdot (\cos\beta - \cos\alpha) \quad (1)$$

According to Eq 1, the uncertainty of absorbed energy is expressed as

$$u_1^2 = \left(\frac{\partial K}{\partial \alpha}\right)^2 u^2(\alpha) + \left(\frac{\partial K}{\partial \beta}\right)^2 u^2(\beta) + \left(\frac{\partial K}{\partial l}\right)^2 u^2(l) + \left(\frac{\partial K}{\partial F}\right)^2 u^2(F) \quad (2)$$

where

$$\frac{\partial K}{\partial \alpha} = F \cdot l \cdot \sin\alpha \quad (3)$$

$$\frac{\partial K}{\partial \beta} = -F \cdot l \cdot \sin\beta \quad (4)$$

$$\frac{\partial K}{\partial l} = F(\cos\beta - \cos\alpha) \quad (5)$$

$$\frac{\partial K}{\partial F} = l \cdot (\cos\beta - \cos\alpha) \quad (6)$$

and $u(\alpha)$, $u(\beta)$, $u(l)$ and $u(F)$ are uncertainties of measured values.

Equation 2 is a summation of uncertainties of measured values but not including uncertainties concerning a machine itself, a specimen, or the environment. Therefore, it is necessary to evaluate uncertainties caused by factors x_i other than α, β, l, and F,

$$u_2^2 = \sum u^2(x_i) \tag{7}$$

and add this term to the estimation of overall uncertainty. Then the uncertainty in the direct verification is expressed as the summation of Eqs 2 and 7,

$$u_1^2 + u_2^2 \tag{8}$$

On the other hand, the indirect verification is also carried out to evaluate the random error, which includes the repeatability of the machine and the uniformity of specimens. If n specimens are used for the indirect verification, the average absorbed energy and its variance are expressed as

$$\overline{K} = \frac{1}{n}\sum_{i=1}^{n} K_i \tag{9}$$

$$\sigma^2 = \frac{1}{n-1}\sum_{i=1}^{n}(K_i - \overline{K})^2 \tag{10}$$

Since the reference value of specimens is the expressed as the average of batch, the term to be added to the overall uncertainty is

$$u_3 = \frac{\sigma}{\sqrt{n}} \tag{11}$$

As a result, expanded uncertainty U of the reference specimens can be calculated with the following equation,

$$U = k \cdot u_C = k \cdot \sqrt{u_1^2 + u_2^2 + u_3^2} \tag{12}$$

where u_C is the combined standard uncertainty, and k is a coverage factor and assumed to be $k = 2$ in many cases. Components in Eq 12, i.e., u_1, u_2, and u_3, represent the uncertainty estimated from the principle of the test method, the direct verification of machines, and the indirect verification with reference specimens, respectively.

Uncertainty Sources Evaluated in the Direct Verification

Components of the uncertainty u_2, which is estimated through the direct verification, can be classified into three groups. The first group is the items numerically evaluated with measuring devices, and their uncertainties can be expressed by the standard deviation. In this study, specimen width b and ligament length $w-a$ are treated in this way.

Verification data of reference specimens are reported by the manufacturer. Table 1 shows the typical results of a batch of specimens obtained with 20 samples. It is found in the table that there are two types of errors, i.e., the deviation around the average value and the bias of average value from the specified value. The concept to estimate uncertainty described in GUM [7] is based on symmetrical distributions around the average values, and the treatment of bias is not suggested because biases should be corrected before the measurement. In some kinds of industrial units of measurement, however, it is not available to correct the bias. In such cases, the bias is recommended to include into the uncertainty as a practical solution (an example of the treatment can be seen in ISO draft for hardness test [8]). In this paper, the following method is used to reduce these two components to one number. The uncertainty assumed to be expressed as the square root of the variance around the specified value,

$$u(b) = \sqrt{(\bar{b} - b_0)^2 + \sigma_b^2} = \sqrt{(10.020 - 10)^2 + 0.007^2} = 0.0212\text{, mm} \qquad (13)$$

where $b_0 = 10$ mm is the specified value, $\bar{b} = 10.020$ mm is the average value, and $\sigma_b = 0.007$ is the standard deviation.

TABLE 1—*Typical verification data of specimen geometry.*

	Specified Value	Average	Standard Deviation
Width b, mm	10	10.020	0.007
Height w, mm	10	10.012	0.007
Notch depth a, mm	2	2.022	0.013

In the same way, the uncertainty of ligament length can be calculated. When $w_0 = 10$ mm is the specified value, $\bar{w} = 10.020$ mm is the average value, and $\sigma = 0.007$ is the standard deviation; the uncertainty of ligament length $w - a$ is

$$\begin{aligned} u(w-a) &= \sqrt{\left\{(\bar{w} - \bar{a}) - (w_0 - a_0)\right\}^2 + \sigma_w^2 + \sigma_a^2} \\ &= \sqrt{\left\{(10.012 - 2.022) - (10 - 2)\right\}^2 + 0.007^2 + 0.013^2} = 0.0178\text{, mm} \end{aligned} \qquad (14)$$

The sensitivity coefficients concerning specimen geometry can be derived assuming that the absorbed energy is proportional to the area of cross-section of specimens, i.e.,

$$\frac{\partial K}{\partial b} = \frac{K}{b}, \quad \frac{\partial K}{\partial (w-a)} = \frac{K}{w-a} \qquad (15)$$

The second group is the items which are verified with limit gauges whether the items are in the permissible range or not. For such items, the uncertainties are estimated assuming that the distribution of probability is rectangular between the upper limit and the lower limit of the permissible range [7]. Items and their uncertainty are listed in Table 2.

In this table, *radius of striker* is not included. The effect of this item can be negligible when the only one type of striker, i.e., 2-mm striker is used every time.

The third group is the items which seem to be significant but are difficult to evaluate in any ways. Examples are *fixture to the base*, *stiffness of framework*, and so on. In the present state these items cannot be included in the budget of uncertainty.

The contribution to the absorbed energy of an item x_i is derived by multiplying its uncertainty $u(x_i)$ and corresponding sensitivity coefficient c_i,

$$u_i^2(K) = c_i^2 \cdot u^2(x_i) \qquad (16)$$

The sensitivity coefficients can be obtained in experiments that were planned to include known errors and statistical analyses. These experiments were carried out by national metrology institutes (NMIs) in some countries [9–11].

TABLE 2—*Estimated uncertainties for the items of the second group.*

Source x_i	Tolerance (Reference)		Uncertainty $u(x_i)$	Reference for Sensitivity
Fall angle α [º]	±0.4	(ISO 148-2, 9.1)	0.231	Eq 3
Rise angle β [º]	±0.4	(ISO 148-2, 9.2)	0.231	Eq 4
Distance between the center of percussion and the axis of rotation, l [mm]	±0.2 %	(ISO 148-2, 9.1)	0.982[b]	Eq 5
Force exerted by the pendulum on the force-proving device for distance l, F [N]	±0.2 %	(ISO 148-2, 9.1)	0.447[c]	Eq 6
Distance between the planes containing support surfaces [mm]	0-0.1	(ISO 148-2, 10.1)	0.0289	Ref. [9][d]
Distance between the planes containing anvil surfaces [mm]	0-0.1	(ISO 148-2, 10.2)	0.0289	Ref. [9][d]
Distance between anvils [mm]	0-0.1	(ISO 148-3, 5.1.1)	0.0289	Ref. [9][d]
Angle of taper of anvils [º]	±1	(ISO 148-3, 5.1.1)	0.577	Ref. [9][d]
Radius of anvils [mm]	0-0.1	(ISO 148-3, 5.1.1)	0.0289	Ref. [9][d]
Distance of striking edge from plane of symmetry of anvils [mm]	±0.25	(ISO 148-3, 5.1.1)	0.144	Ref. [9][d]
Test temperature [ºC]	±1	(ISO 148-1, 8.2.1)	0.289	Ref. [10][de]
Distance between the center of specimens and the center of striker [mm]	0-0.3[a]		0.0866	Ref. [10][de]
Impact velocity [m/s]	0-0.5	(ISO 148-2, 9.3)	0.144	Ref. [11][f]

[a] Estimated from tolerances of anvil and tong.
[b] $l = 850.2$ for the NMIJ machine.
[c] $F = 386.911$ for the NMIJ machine.
[d] The values of sensitivity are not described in the reference, but they are calculated from the data in the same experiments.
[e] The sensitivity was estimated in the range of 30–120 J levels. It is assumed that the sensitivity for 160 J level is same with this value.
[f] The sensitivity was estimated with a different type of impact machine. It is assumed that the sensitivity does not depend on machine design.

Uncertainty Evaluated in the Indirect Verification

It is possible to evaluate the repeatability of measurement by analyzing routine check data of Charpy machine. Figure 2 shows the repeatability of measurement in five sets of routine checks during two years with 110 specimens. In this figure significant differences between sets of measurement can be found because the specimens of several batches were used for these measurements. In order to separate the repeatability in single set of measurement from other factors, i.e., the difference between batches and the long-term stability of the machine. The analyses of variance of one-way layout were carried out. The results are shown in Table 3. The repeatability of the measurement is 2.33 %, 2.38 %, and 3.23 % for 30, 100, and 160 J levels, respectively. These values include the homogeneity of the batch of specimens and the short-term stability of the machine, and these two effects cannot be separated.

The long-term stability of the machine depends on the maintenance of the machine, and its effects are already taken into account when the uncertainty sources in the direct verification are estimated. Therefore, this term is not included in the uncertainty budgets shown in the next section.

In order to estimate the long-term stability, it is necessary to collect measurement results with specimens of the same batch for a certain period. For the NMIJ machines, this effect was obtained in the measurement for the international comparisons [12], and it was estimated as 0.66–2.16 % for three years (Table 4).

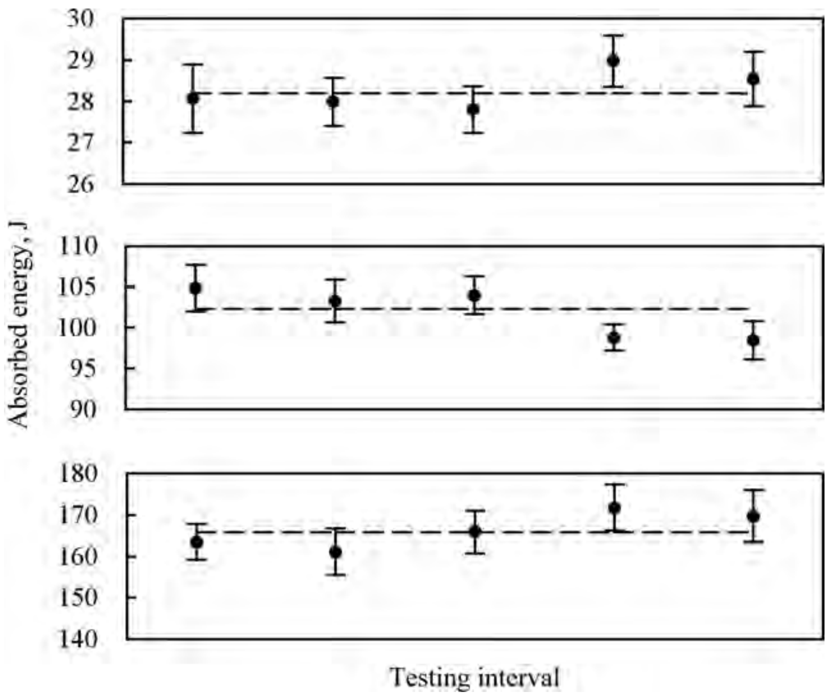

FIG. 2—*Results of the routine check of the standard Charpy machine.*

TABLE 3—*Repeatability of measurement.*

	30 J level	100 J level	160 J level
Average, J	28.19	102.29	165.69
Standard deviation, J	0.658 (2.33 %)	2.430 (2.38 %)	5.354 (3.23 %)
Standard deviation of the mean of 25 measurements, J	0.132 (2.33 %)	0.486 (2.38 %)	1.071 (3.23 %)

TABLE 4—*Stability of measurement for three years.*

	15 J level		30 J level		100 J level	
Machine	NMIJ 1	NMIJ 2	NMIJ 1	NMIJ 2	NMIJ 1	NMIJ 2
Average, J	15.76	15.87	26.05	26.36	99.15	98.92
Standard deviation, J	0.15	0.29	0.56	0.57	1.03	0.65
Relative S. D.	2.33 %	1.81 %	2.16 %	2.15 %	1.04 %	0.66 %

Uncertainty Budgets

The budget of measurement uncertainty is estimated from the procedure mentioned in the previous section and worksheets for 30, 100, and 160 J levels are shown in Tables 5–7.

TABLE 5—*Uncertainty budget for 30 J level.*

Source x_i	Type	Uncertainty $u(x_i)$	Distribution	Sensitivity Coefficient c_i	$u_i(K)$ [J]
Fall angle α [º]	B	0.231	Rectangular	3.50	0.809
Rise angle β [º]	B	0.231	Rectangular	-4.09	0.945
Distance between the center of percussion and the axis of rotation, l [mm]	B	0.982	Rectangular	0.353	0.035
Force exerted by the pendulum on the force-proving device for distance l, F [N]	B	0.447	Rectangular	0.0775	0.035
Distance between the planes containing support surfaces [mm]	B	0.0289	Rectangular	0.0301	0.001
Distance between the planes containing anvil surfaces [mm]	B	0.0289	Rectangular	0.507	0.015
Distance between anvils [mm]	B	0.0289	Rectangular	-0.133	0.004
Angle of taper of anvils [º]	B	0.577	Rectangular	-0.0218	0.013
Radius of anvils [mm]	B	0.0289	Rectangular	-1.11	0.032
Distance of striking edge from plane of symmetry of anvils [mm]	B	0.144	Rectangular	0.547	0.079
Specimen width, b [mm]	A	0.0212	Normal	3.00	0.064
Ligament length, $w-a$ [mm]	A	0.0178	Normal	3.75	0.067
Test temperature [ºC]	B	0.289	Rectangular	0.330	0.095
Distance between the center of specimens and the center of striker [mm]	B	0.0866	Rectangular	2.00	0.173
Impact velocity [m/s]	B	0.144	Rectangular	0.143	0.021
Repeatability [J]	A	0.132	Normal	1.00	0.132
Combined standard uncertainty, u_C [J]					1.274 (4.25 %)
Expanded uncertainty, U ($k=2$) [J]					2.549 (8.50 %)

TABLE 6—*Uncertainty budget for 100 J level.*

Source x_i	Type	Uncertainty $u(x_i)$	Distribution	Sensitivity Coefficient c_i	$u_i(K)$ [J]
Fall angle α [º]	B	0.231	Rectangular	3.50	0.809
Rise angle β [º]	B	0.231	Rectangular	-5.01	1.157
Distance between the center of percussion and the axis of rotation, l [mm]	B	0.982	Rectangular	0.118	0.115
Force exerted by the pendulum on the force-proving device for distance l, F [N]	B	0.447	Rectangular	0.258	0.115
Distance between the planes containing support surfaces [mm]	B	0.0289	Rectangular	-3.06	0.088
Distance between the planes containing anvil surfaces [mm]	B	0.0289	Rectangular	-1.48	0.043
Distance between anvils [mm]	B	0.0289	Rectangular	-2.40	0.069
Angle of taper of anvils [º]	B	0.577	Rectangular	-1.77	1.023
Radius of anvils [mm]	B	0.0289	Rectangular	-8.41	0.243
Distance of striking edge from plane of symmetry of anvils [mm]	B	0.144	Rectangular	1.61	0.232
Specimen width, b [mm]	A	0.0212	Normal	10.0	0.212
Ligament length, $w-a$ [mm]	A	0.0178	Normal	12.5	0.223
Test temperature [ºC]	B	0.289	Rectangular	0.330	0.095
Distance between the center of specimens and the center of striker [mm]	B	0.0866	Rectangular	2.00	0.173
Impact velocity [m/s]	B	0.144	Rectangular	0.143	0.021
Repeatability [J]	A	0.486	Normal	1.00	0.486
Combined standard uncertainty, u_C [J]					1.888 (1.89 %)
Expanded uncertainty, U ($k=2$) [J]					3.776 (3.78 %)

TABLE 7—*Uncertainty budget for 160 J level.*

Source x_i	Type	Uncertainty $u(x_i)$	Distribution	Sensitivity Coefficient c_i	$u_i(K)$ [J]
Fall angle α [º]	B	0.231	Rectangular	3.50	0.809
Rise angle β [º]	B	0.231	Rectangular	-5.47	1.262
Distance between the center of percussion and the axis of rotation, l [mm]	B	0.982	Rectangular	0.188	0.185
Force exerted by the pendulum on the force-proving device for distance l, F [N]	B	0.447	Rectangular	0.414	0.185
Distance between the planes containing support surfaces [mm]	B	0.0289	Rectangular	-0.969	0.028
Distance between the planes containing anvil surfaces [mm]	B	0.0289	Rectangular	-1.843	0.053
Distance between anvils [mm]	B	0.0289	Rectangular	-5.16	0.149
Angle of taper of anvils [º]	B	0.577	Rectangular	-3.27	1.888
Radius of anvils [mm]	B	0.0289	Rectangular	-17.4	0.501
Distance of striking edge from plane of symmetry of anvils [mm]	B	0.144	Rectangular	7.86	1.135
Specimen width, b [mm]	A	0.0212	Normal	16.0	0.339
Ligament length, $w-a$ [mm]	A	0.0178	Normal	20.0	0.357
Test temperature [ºC]	B	0.289	Rectangular	0.330	0.095
Distance between the center of specimens and the center of striker [mm]	B	0.0866	Rectangular	2.00	0.173
Impact velocity [m/s]	B	0.144	Rectangular	0.143	0.021
Repeatability [J]	A	1.071	Normal	1.00	1.071
Combined standard uncertainty, u_C [J]					2.979 (1.86 %)
Expanded uncertainty, U ($k=2$) [J]					5.958 (3.72 %)

Discussion

As shown in Tables 5–7, the combined standard uncertainties are estimated to be 1.274 J (4.25 %), 1.888 J (1.89 %), and 2.979 J (1.86 %) for 30, 100, and 160 J levels, respectively. This result shows that the absolute value of uncertainty is getting greater with the energy level of specimen, however the relative value of uncertainty is getting smaller. The contribution of uncertainty sources is illustrated in Figs. 3–5 as the ratios between squares of uncertainties, $u_i^2(x_i)$. At the 30 J level, the contributions of *fall angle* and *rise angle* are quite significant, because the difference of angles is smaller at a lower energy level, and the error of readings of the dial causes larger difference of absorbed energy. In those calculations, the uncertainty of angle measurement is estimated with the tolerance of ±0.4º because there are no evidences for the accuracy of the dial. However, the scale interval of dial is 0.2º, and if we trust this scale the uncertainty of angle measurement will be reduced to 1/4 . In this case, the contributions of other factors will be increased, and some factors may be significant. The contribution of *repeatability* is greater at a higher energy level. At the higher energy levels, *angle of taper of anvils* and *distance of striking edge from plane of symmetry of anvils* are significant. In such energy levels, the larger plastic deformation occurs in a specimen, and it increases the friction between a specimen and anvils and also increases the absorbed energy.

Estimated standard uncertainties are greater than the long-term stabilities of the standard machines (Table 4). Therefore, the conditions of the machine, which are evaluated by the direct verification, can be regarded as a reason of the long-term stability of the machine. However, the difference between the reference machines, which are found in the international comparison, is more than the estimated uncertainties [3]. It means that the bias between different types of machines cannot be explained by the conditions of machines, and it suggests the other significant factors, e.g., *striker type*, *stiffness of frame*, *fixture to the base*, etc.

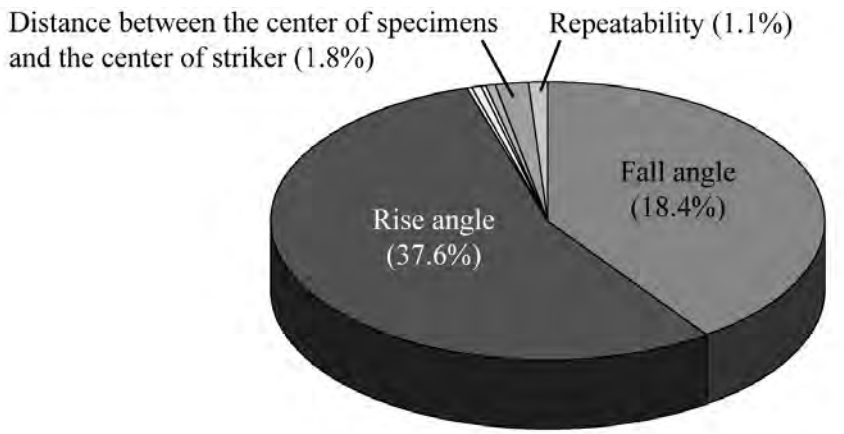

FIG. 3—*Contribution of uncertainty sources at the 30 J level (the ratio between squares of uncertainties,* $u_i^2(x_i)$*).*

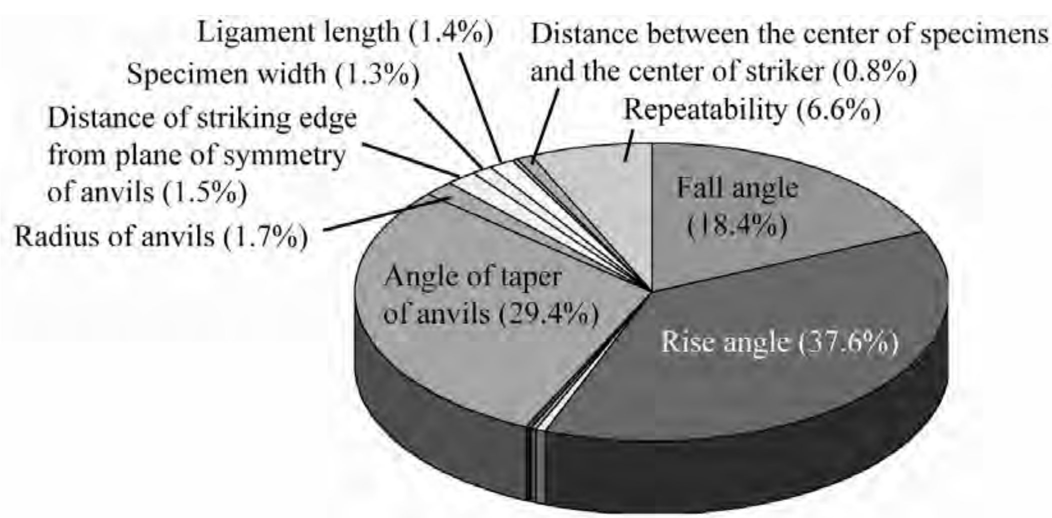

FIG. 4—*Contribution of uncertainty sources at 100 J level (the ratio between squares of uncertainties,* $u_i^2(x_i)$*).*

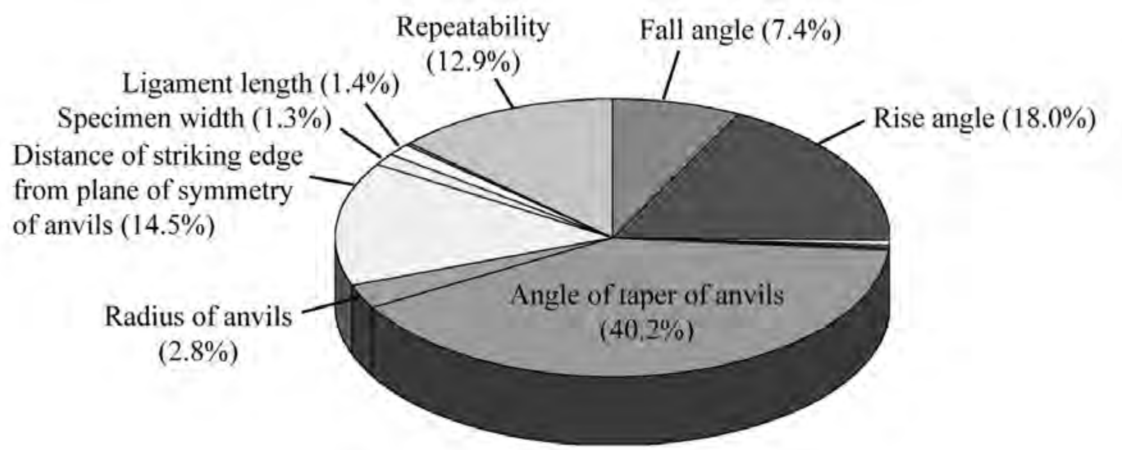

FIG. 5—*Contribution of uncertainty sources at 160 J level (the ratio between squares of uncertainties,* $u_i^2(x_i)$*).*

Conclusion

In this study, the uncertainties of the reference values of the impact test specimens are estimated at 30, 100, and 160 J levels. Even for the national standard machines, it is not enough to consider the repeatability of measurement for the estimation of measurement uncertainty because the measured values with different types of standard machines are deviated more than their repeatability. To investigate this situation, the uncertainty was estimated as the combination of results of direct and indirect verification.

According to the analyses of the contributions of uncertainty sources, the *repeatability* of measurement is a significant effect at all levels, and its contribution is greater at a higher energy level. The effects of *fall angle* and *rise angle* are significant, and their contribution is greater at a lower energy level. The effects of *angle of taper of anvils* and *distance of striking edge from plane of symmetry of anvils* are significant at higher energy levels.

The factors evaluated in the direct verification are connected with absorbed energy by considering respective sensitivity coefficients and reflect machine conditions, which cause systematic errors on measured values. From the investigation of the results of the routine check of the machine or the international comparison, it is found that estimated uncertainties can explain the long-term stability of the machines but cannot explain the bias between different types of machines.

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Journal of ASTM International, March 2006, Vol. 3, No. 3
Paper ID JAI13106
Available online at www.astm.org

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Analysis of Charpy Impact Verification Data: 1993–2003

ABSTRACT: Indirect verification tests used to verify the performance of Charpy impact machines according to ASTM Standard E23 were evaluated by the National Institute of Standards and Technology (NIST), and the data from these tests are collected in a database. The data include the capacity and the pendulum design of the impact machine, the energy obtained for each specimen tested, the reference energy for the specimen lot tested, and the test date. The principal use of this data is to track the performance of individual impact machines. However, the data also provide an opportunity to evaluate existing and proposed requirements for the indirect verification of Charpy impact machines. The results of more than 16 000 verification tests are used to compare the current verification requirements of ASTM Standard E23 with those of ISO Standard 148-2. Discussions focus on the identification of reasonable, practical, and meaningful verification requirements that might be proposed for use in both documents.

KEYWORDS: Charpy V-notch, impact certification program, impact testing, notched-bar testing, pendulum impact machines, reference specimens

Introduction

The Charpy impact machine verification program has been administered by the National Institute of Standards and Technology (NIST) since 1989 [1]. NIST's role in the program is to procure and characterize batches of verification specimens, and to distribute verification specimens to customers who wish to verify their Charpy machines. After the customer tests the five verification specimens, the resulting data and broken specimens are returned to NIST to determine whether or not the customer's machine is consistent with requirements of ASTM Standard E-23 [2]. A database containing the results of verification tests and associated machine information is maintained by NIST to track individual Charpy machines and to monitor the verification program.

The main purpose of this study is to examine the properties of ASTM Standard E23 and ISO Standard 148-2 [3] for Charpy machine verification rules. We investigate existing rules and some proposed extensions to the ASTM rules, such as the adoption of a rule limiting the variation in verification tests. Historical data from the Charpy V-notch machine verification program administered by NIST are used to compare the rules of interest. We also compare two different pendulum types and investigate the effect of machine capacity on the performance of ASTM verification rules. Finally, we compare ASTM passing rates based on country affiliation.

It is necessary to define some quantities before describing the verification limits under study.

- Reference energy value: k_R
- Pooled standard deviation of the pilot lot: S_P
- Customer average: k_C
- Difference: $d=|k_C-k_R|$
- Normalized difference: $d_n=|k_C-k_R|/k_R$
- Customer range: R
- Normalized range: $R_n=R/k_R$
- Customer standard deviation: S_C

The reference energy value for a single batch of impact specimens is determined by testing 25 specimens on each of three NIST reference machines. The reference value is the average absorbed energy

Manuscript received November 3, 2004; accepted for publication October 17, 2005; published December 2005. Presented at ASTM Symposium on Pendulum Impact Machines: Procedures and Specimens on 8 November 2004 in Washington, DC; T. A. Siewert, M. P. Manahan, C. N. McCowan, and D. Vigliotti, Guest Editors.
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TABLE 1—*Verification limits to define "passing" Charpy machines.*

Verification rule	Low energy	High and super-high energy
ASTM	$d \leq 1.4$ J	$d_n \leq 5$ %
ASTM A	$d \leq 1.4$ J and $R \leq 5$ J	$d_n \leq 5$ % and $R \leq 15$ J
ASTM B	$d \leq 1.4$ J and $R_n \leq 25$ %	$d_n \leq 5$ % and $R_n \leq 25$ %
ISO—Reference machines	$d \leq 2$ J and $R \leq 3$ J	$d_n \leq 5$ % and $R_n \leq 7.5$ %
ISO—Industrial machines	$d \leq 4$ J and $R \leq 6$ J	$d_n \leq 10$ % and $R_n \leq 15$ %

for the 75 tests. The pooled standard deviation of the pilot lot is needed for an alternative verification limit which we call Wang's rule [4]. See Appendix A for information regarding the calculation of S_P. The customer average is the average absorbed energy for five verification specimens.

A customer's results based on five verification tests must meet certain requirements before the customer's machine can be verified. Table 1 lists current ASTM and ISO verification limits as well as two proposed additions to the ASTM limits, which we will refer to as ASTM A and ASTM B [5]. ASTM A and ASTM B attempt to control customer variation by imposing limits to the range and normalized range, respectively.

The reason for limiting customer variation is to ensure a certain degree of precision so that test results are fairly repeatable. For all analyses presented in this document, we assume the data were independent even though some machines were tested multiple times at each energy level.

Stability over Time

Before examining verification limits, we need to determine the stability of the verification program over time. Figure 1 displays differences or normalized differences between customer averages and reference values over time for each energy level. ASTM, ISO reference machine, and ISO industrial machine limits are displayed on each plot (the ASTM and ISO reference machine limits are the same for high and super-high energy). The differences represent customer data observed from January 1993 to November 2003 for each energy level. The plots indicate that the differences are stable over time for all energies.

Passing Rates

We compared the various verification limits defined in Table 1 by applying them to historical customer data retrospectively and computing pass/fail rates. The results are listed in Table 2. Also shown in Table 2 are results for ISO industrial and ISO reference machine rules when the range and normalized range rules are ignored so that only the energy limits are used to determine pass/fail rates. (For high and super-high energies, the ISO reference machine limits are the same as the ASTM limits when the normalized range rules are ignored.)

The results in Table 2 indicate the following:

- Passing rates for ISO industrial machine rules at all energy levels are extremely high.
- Virtually all machines pass ISO industrial machine rules if we ignore the range rules and consider only the energy limits.
- ISO reference machine range rules are very stringent for high and super-high energies.
- Low energy passing rates are similar (about 88 %) for the various ASTM rules considered and the ISO reference machine rule, but the passing rate for the ISO industrial machine rule is substantially higher.
- At low energy, adding the proposed range or normalized range rule does not substantially change passing rates, although the ASTM A rule fails a few additional machines with high variation.
- At high energy, passing rates are nearly identical for ASTM and ASTM B. ASTM A fails a few machines with high variation.
- For super-high energy, the ASTM A limits are too strict, while the ASTM B limits produce nearly the same results as the ASTM rule.

Yearly passing rates at each energy level were computed based on the historical customer data (Fig. 2) for the five verification rules. Passing rates for the existing ASTM rules (represented by stars in the figures) appear to be fairly stable with the exception of 1999 at the Low energy level.

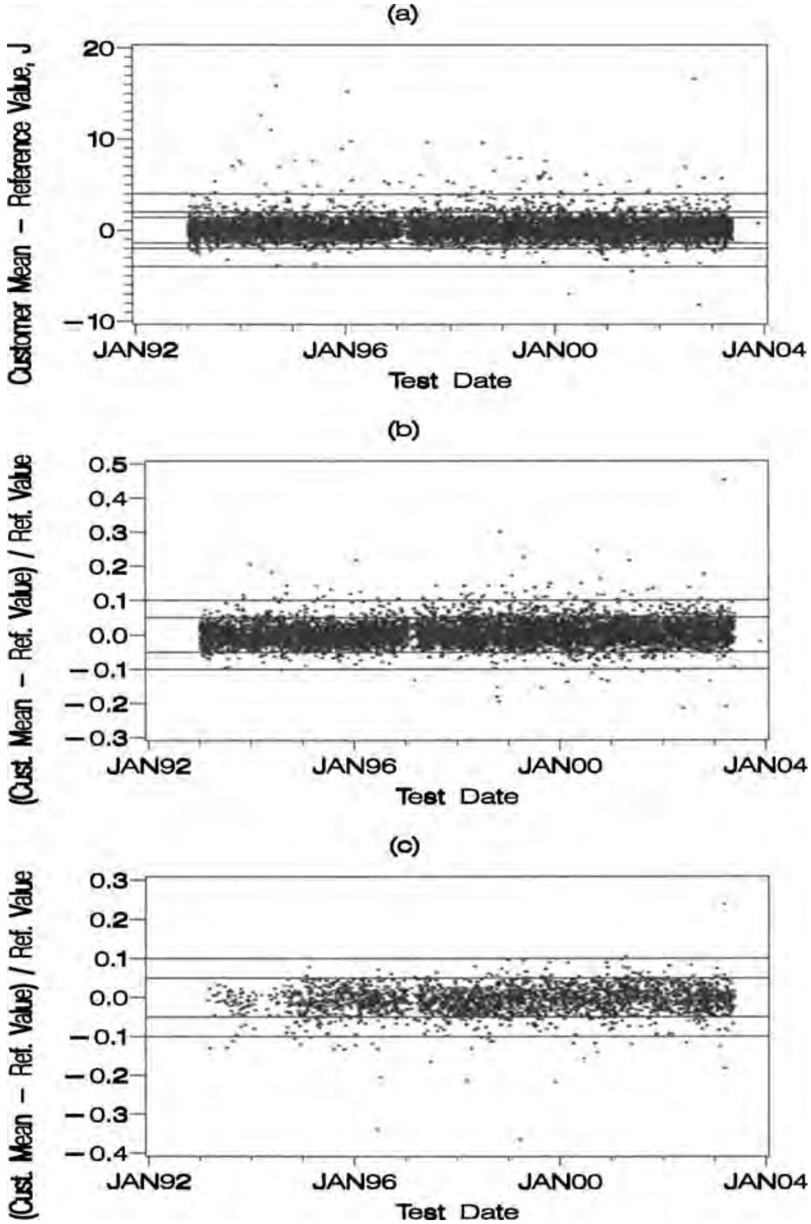

FIG. 1—*(a) Plot of differences over time for Low energy. ASTM, ISO reference machine, and ISO industrial machine energy limits are displayed (1.4, 2, and 4 J, respectively). (b) High energy and (c) Super-high energy normalized differences over time. ASTM, ISO reference machine, and ISO industrial machine energy limits are displayed (5, 5, and 10 %, respectively).*

Plots of all customer deviations versus their ranges (R) or normalized ranges (R_n) are shown in Fig. 3. The various acceptance limits from Table 1 are displayed on each plot. The plots indicate that many machines with large variation are certified using the ASTM criteria for all energy levels. Also, the arbitrary range and normalized range limits for ASTM A and ASTM B, respectively, should be adjusted so that they are more realistic with respect to the data. For example, a reasonable limit might be the 95th percentile of the historical customer ranges so that machines with the largest 5 % of variation would be failed. Histograms of customer ranges for each energy level are shown in Fig. 4. The 95th percentiles are indicated with a vertical dashed line.

The new verification rules, based on current ASTM limits in conjunction with range restrictions defined by the 95th percentiles of customer ranges, will be called ASTM C and ASTM D for the absolute range rule and relative range rule, respectively. Using the 95th percentiles as limits to the range and normalized range produces the pass/fail rates shown in Table 3.

Failing machines with the largest 5 % of ranges produces pass/fail rates that are similar across energy

TABLE 2—*Passing and failing rates for verification limits.*

	Pass	Fail	Total
Low energy			6955 (100 %)
ASTM	6146 (88.4 %)	809 (11.6 %)	
ASTM A	6101 (87.7 %)	854 (12.3 %)	
ASTM B	6023 (86.6 %)	932 (13.4 %)	
ISO—Reference machines	6120 (88.0 %)	835 (12 %)	
ISO—Industrial machines	6862 (98.7 %)	93 (1.3 %)	
ISO—Reference machines Energy Limit only	6567 (94.4 %)	388 (5.6 %)	
ISO—Industrial machines Energy Limit only	6893 (99.1 %)	62 (0.9 %)	
High energy			6938 (100 %)
ASTM	6302 (90.8 %)	636 (9.2 %)	
ASTM A	6196 (89.3 %)	742 (10.7 %)	
ASTM B	6301 (90.8 %)	637 (9.2 %)	
ISO—Reference machines	4042 (58.3 %)	2896 (41.7 %)	
ISO—Industrial machines	6706 (96.7 %)	232 (3.3 %)	
ISO-Reference machines Energy Limit only	6302 (90.8 %)	636 (9.2 %)	
ISO—Industrial machines Energy Limit only	6856 (98.8 %)	82 (1.2 %)	
Super-High energy			2426 (100 %)
ASTM	2191 (90.3 %)	235 (9.7 %)	
ASTM A	1015 (41.8 %)	1411 (58.2 %)	
ASTM B	2185 (90.1 %)	241 (9.9 %)	
ISO—Reference machines	1186 (48.9 %)	1240 (51.1 %)	
ISO—Industrial machines	2274 (93.7 %)	152 (6.3 %)	
ISO-Reference machines Energy Limit only	2191 (90.3 %)	235 (9.7 %)	
ISO—Industrial machines Energy Limit only	2392 (98.6 %)	34 (1.4 %)	

levels and decreases passing rates by at most 4.2 %. Annual passing rates for each energy level for the existing ISO and ASTM limits, as well as ASTM limits with proposed range rules based on 95th percentiles of the range, are shown in Fig. 5.

We computed correlations between energy levels based on relative ranges for machines in which specimens for two or more energy levels were tested on the same day. The analyses did not indicate that machines with high variation at one energy level would also have high variation at other energy levels. The correlation between low energy relative ranges and high energy relative ranges is 0.12, between high energy and super-high energy relative ranges is 0.11, and between low energy and super-high energy relative ranges is 0.06.

Wang's Verification Rule

One disadvantage to using a fixed range or normalized range rule is that it does not take into account variation in the pilot lot. Acceptance limits have been proposed by Wang that minimize the probability of failing a good machine and that account for pilot lot variation. First, we perform a test to determine whether the variance of the candidate machine data is the same as the variation in the pilot lot (Appendix B), and second, we compare the candidate machine mean to limits that account for variation. The candidate machine must pass both rules to be certified. The difference d between the candidate machine mean and the reference value must fall within

$$U = -L = (D + 0.4619 \cdot S \cdot t_{1-\alpha:76})\ J, \tag{1}$$

where $S^2=(72\ S_P^2+4\ S_C^2)/76$, $t_{1-\alpha:76}$ is the $100(1-\alpha)$th percentile of Student's t distribution with 76 degrees of freedom, and D is the amount of allowable deviation between the customer's mean and the reference value. The value of D is arbitrary and depends on engineering judgment. For illustrative purposes, we will choose D=1.4 J for low energy, D=6.0 J for high energy, and D=12.0 J for super-high

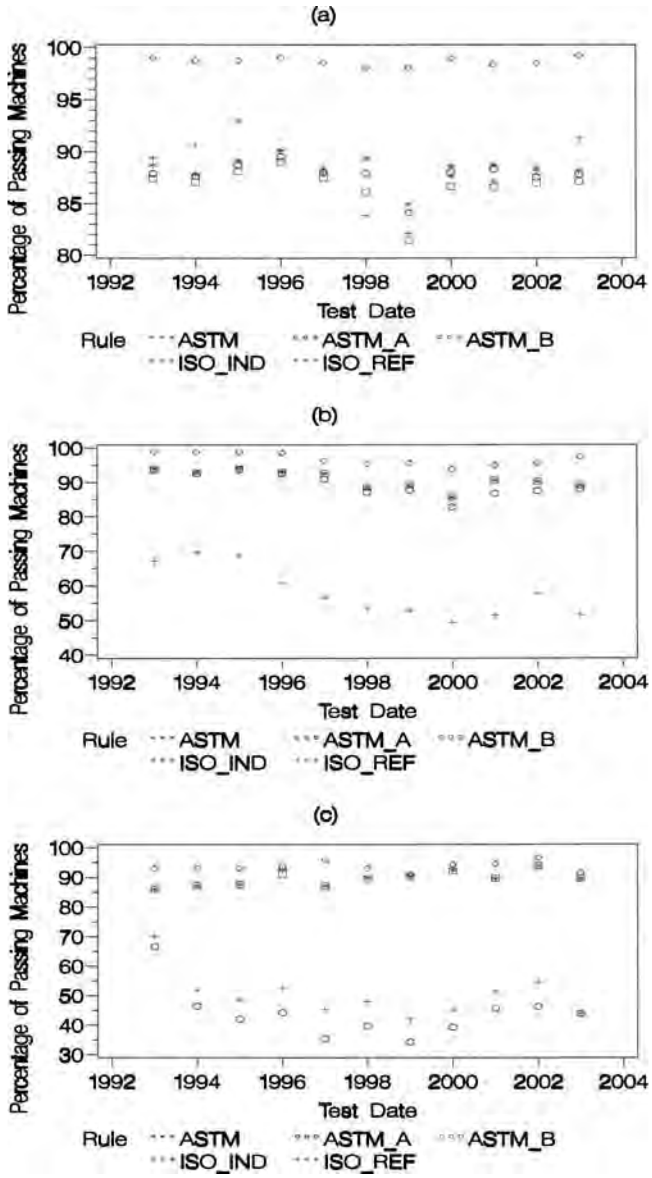

FIG. 2—*Annual passing rates for various verification rules at (a) low energy, (b) high energy, and (c) super-high energy.*

energy. The high and super-high energy values of D approximate 5 % limits based on the largest observed reference values, respectively. Table 4 displays pass/fail rates for each energy level based on Wang's rule. Not all pilot lot data were available to match with customer data, so the total number of observations is less than in previous analyses. Also, pilot lot sample sizes for individual reference machines were not available, so they are assumed to be equal.

The low energy passing rate in Table 4 is slightly higher than those listed in Table 3. However, the high and super-high passing rates are extremely low mainly because the variability in pilot lots is much smaller than customer variability. A histogram of customer standard deviations for super-high energy is shown in Fig. 6. The average observed standard deviation for super-high pilot lots is about 2.6 J, while customer variability averages 7.0 J. The discrepancy is less for high energy, where pilot lot standard deviations average 1.7 J and customer standard deviations average 2.8 J. Large customer variability is disturbing because it indicates that customer's measurements are not repeatable.

Simulation Study

To compare the performance of different verification rules, we simulated pilot lot and customer data and computed passing rates for low, medium, and high variation for each energy level. The simulated data had

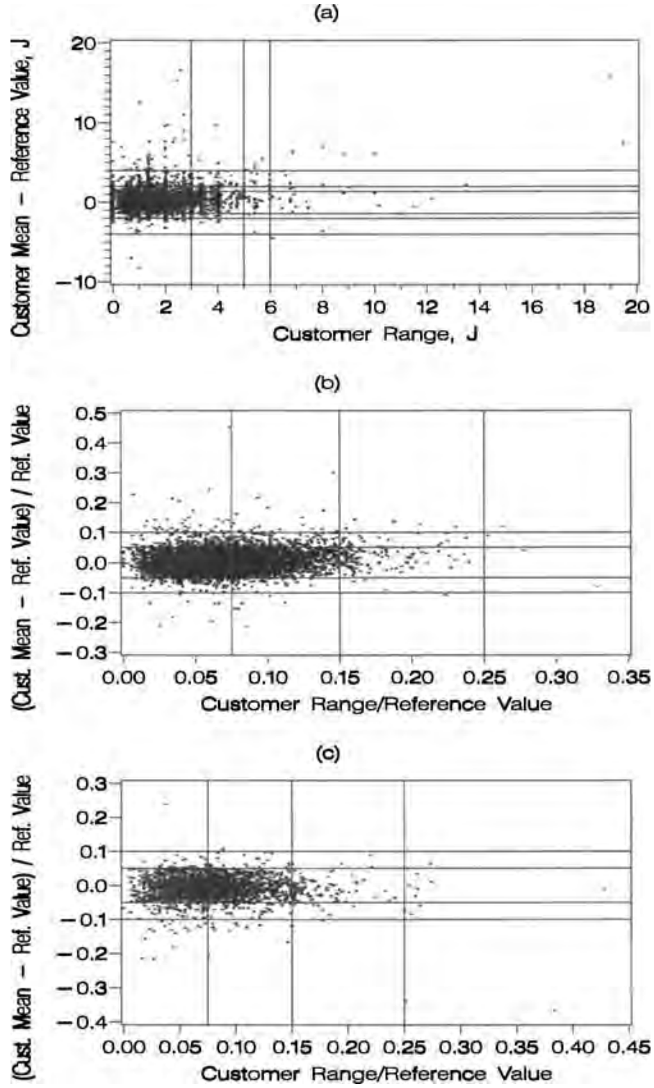

FIG. 3—*(a) Differences versus customer ranges for low energy specimens. Verification limits from Table 1 are represented by vertical and horizontal lines. The range limit for ASTM B is not shown in (a). Normalized differences versus normalized ranges for customers testing (b) high energy and (c) super-high energy specimens. Verification limits from Table 1 are represented by vertical and horizontal lines. The normalized range limits for ASTM A are not shown in (b) and (c).*

equal variance for customers and pilot lots. For each energy level, the verification rules were applied to the same simulated data. The results for all energy levels are displayed in Figs. 7–9. The verification rules of interest are the existing ASTM rule, the ISO reference machine rule, the ASTM rule with range/relative range restrictions based on the 95th percentile of customer ranges, and Wang's rule.

The simulation results indicate that passing rates for all verification rules are sensitive to variation inherent in the measurement system and specimens. When the customer mean is close to the reference value, the lines corresponding to the highest variations in Figs. 7–9 have the lowest passing rates. The high and super-high energy ISO rules for reference machines have very low passing rates with only moderate variation and small differences between the customer's mean and the reference value; however, passing rates for the low energy case are all above 75 % regardless of variation. Adding reasonable range and normalized range rules to the existing ASTM rules improves passing rates, but does not eliminate the influence of specimen and system variation. In contrast, Wang's rule yields nearly identical passing rates for machines falling within the allowable difference D regardless of variation.

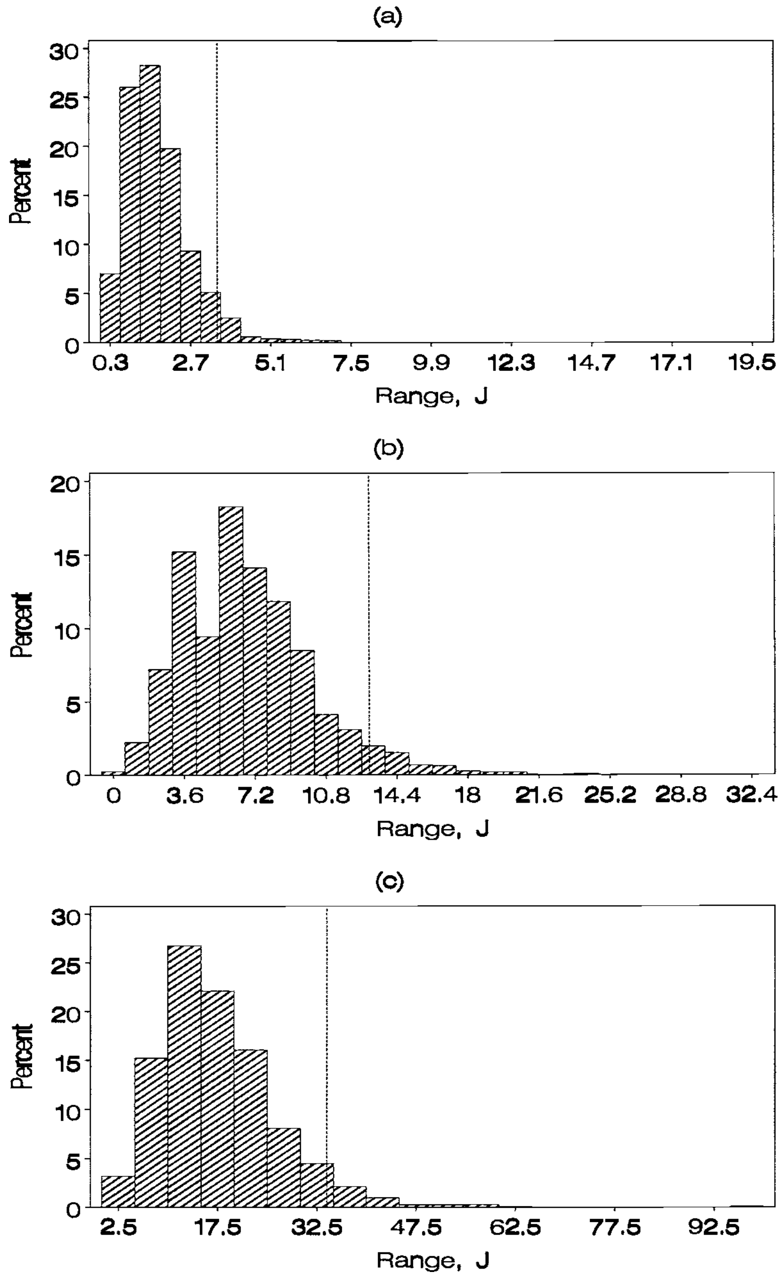

FIG. 4—*(a) Distribution of low energy customer ranges. The 95th percentile is indicated by a dashed vertical line at 3.5 J. (b) Distribution of high energy customer ranges. The 95th percentile is indicated by a dashed vertical line at 13.0 J. (c) Distribution of super-high energy customer ranges. The 95th percentile is indicated by a dashed vertical line at 34.0 J.*

Pendulum Type Comparison

We compared two pendulum types C and U by examining passing rates for the existing ASTM program. Table 5 lists passing rates for each pendulum type and energy level as well as the *P*-value computed for a test comparing the passing rates.

While the observed passing rates for pendulum types are similar at each energy level, the *P*-values indicate that the rates are significantly different. It is common for tests of proportions to produce significant results when sample sizes are large; however, the differences might not be of practical significance.

Other analyses of pendulum type involve comparing mean energy values of machines that pass the existing ASTM verification rules. Calculated average impact energies for each energy level, machine, and lot were categorized according to pendulum type. Two types of analyses were performed using the mean energies and pendulum types: (1) two-sample *t* tests for each energy level and lot separately, and (2) an

TABLE 3—*Passing rates for current ASTM rules and ASTM verification limits using 95th percentile range and normalized range limits.*

	Pass	Fail	Total
Low energy			6955 (100 %)
ASTM	6146 (88.4 %)	809 (11.6 %)	
ASTM C—R ≤ 3.5 J	5914 (85.0 %)	1041 (15.0 %)	
ASTM D—R_n ≤ 23 %	5970 (85.8 %)	985 (14.2 %)	
High energy			6938 (100 %)
ASTM	6302 (90.8 %)	636 (9.2 %)	
ASTM C—R ≤ 13 J	6033 (87.0 %)	905 (13.0 %)	
ASTM D—R_n ≤ 13 %	6022 (86.8 %)	916 (13.2 %)	
Super-high energy			2426 (100 %)
ASTM	2191 (90.3 %)	235 (9.7 %)	
ASTM C—R ≤ 34 J	2102 (86.6 %)	324 (13.4 %)	
ASTM D—R_n ≤ 15 %	2088 (86.1 %)	338 (13.9 %)	

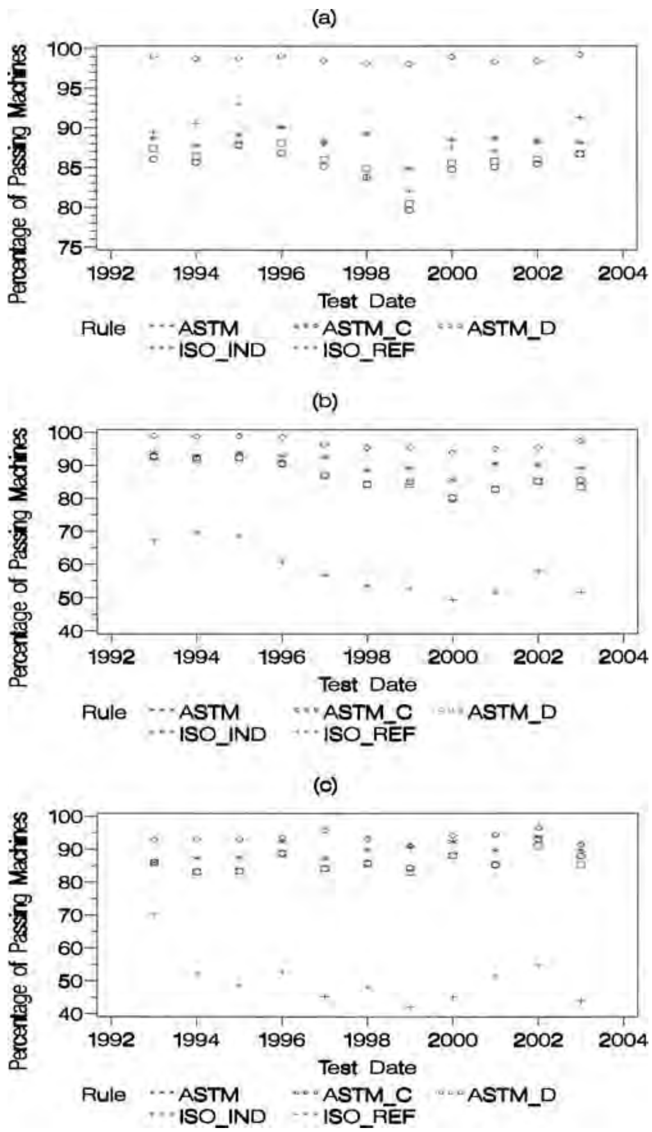

FIG. 5—*Annual passing rates for (a) low energy, (b) high energy, and (c) super-high energy. ASTM C and ASTM D limits are the 95th percentile of low energy customer ranges.*

analysis of variance at each energy level in which we accounted for differences among lots.

Overall, the results of the two-sample *t* tests were inconclusive. Some of the differences between the means of the two pendulum types were significant and some were not, indicating that there is a relationship between pendulum type and lot. In other words, conclusions about differences between the two pendulum types depended on the lot used in the test.

An analysis of variance was performed to determine whether differences between average impact

TABLE 4—*Passing rates for Wang's verification limits. The allowable difference D and the average value of the upper limit U are shown for each energy level.*

Energy level	Pass	Fail	Total
Low (D=1.4 J, U=2.1 J)	5217 (89 %)	665 (11 %)	5882 (100 %)
High (D=6.0 J, U=7.6 J)	2197 (52 %)	2034 (48 %)	4231 (100 %)
Super-high (D=12.0 J, U=14.4 J)	312 (19 %)	1370 (81 %)	1682 (100 %)

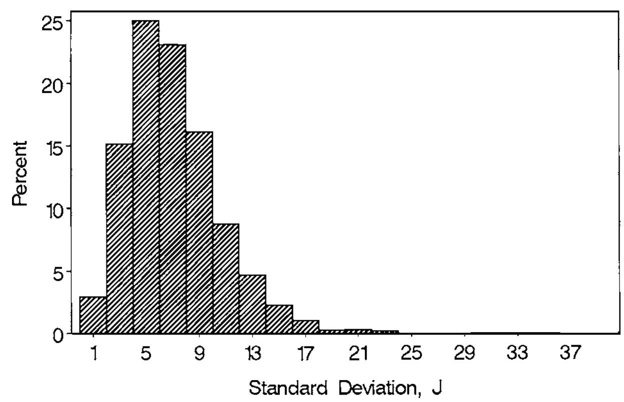

FIG. 6—*Distribution of super-high energy customer standard deviations.*

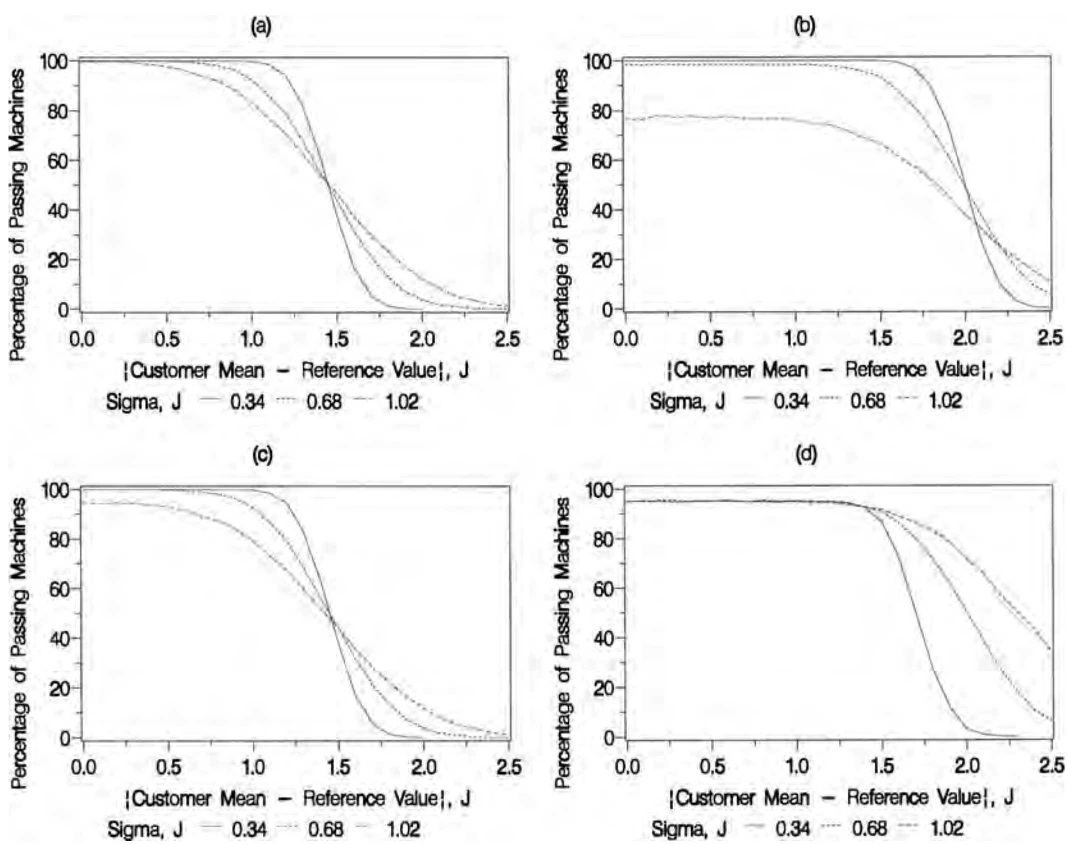

FIG. 7—*(a) Simulation results for the existing low energy ASTM verification rule. (b) Simulation results for the low energy ISO reference machine verification rule. (c) Simulation results for the low energy ASTM rule with range ≤3.5 J. (d) Simulation results for Wang's proposed low energy rule with D=1.4 J.*

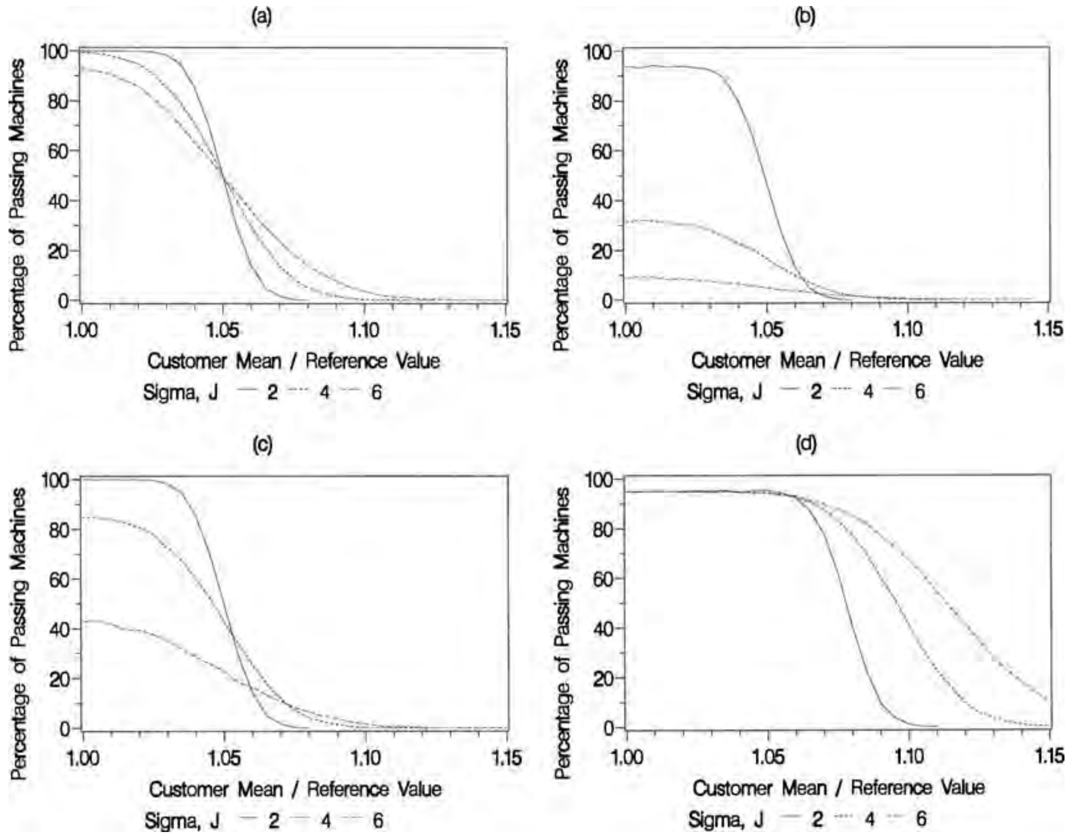

FIG. 8—*(a) Simulation results for the existing high energy ASTM verification rule. (b) Simulation results for the high energy ISO reference machine verification rule. (c) Simulation results for the high energy ASTM rule with relative range ≤13 %. (d) Simulation results for Wang's proposed high energy rule with D = 6 J.*

energies for the two pendulum types were significant after accounting for differences among lots. The analysis of variance results are shown in Table 6.

The *P*-values indicate that means for the two pendulum types are significantly different at the low and high energies, but are not significantly different for super-high energy at the 0.05 level. The analysis of variance also indicated that there is some relationship between pendulum type and lot. Additional work is needed in this area to fully understand the effect of pendulum type and its dependence on lot.

Machine Capacity Analysis

We examined average impact energy and ASTM passing rates associated with the machine capacities reported by customers. We fit a straight line to customer average versus machine capacity for each energy level. Only data associated with machines passing the existing ASTM verification rules were used in the analysis since data from failing machines are unreliable. The graphical results are shown in Fig. 10, and Table 7 displays slopes, *P*-values, and correlation coefficients for each energy level.

The slopes for high and super-high energies were not significantly different from zero, indicating that machine capacity is not a good predictor of the average breaking strength. For low and high energies, higher machine capacities were associated with slightly larger customer averages (positive slope), while higher machine capacities were associated with slightly lower customer averages for super-high energy machines (negative slope).

Although the low energy slope is significantly different from zero, the result may not be of practical significance. The average impact energy for a machine with a 50 J capacity is only 0.63 J less than the average impact energy for a machine with a capacity of 750 J. Also, it is common to achieve a statistically significant result when the sample size is large. Thus, it is left to engineering judgment as to whether average impact energy is increasing as machine capacity increases at the low energy level.

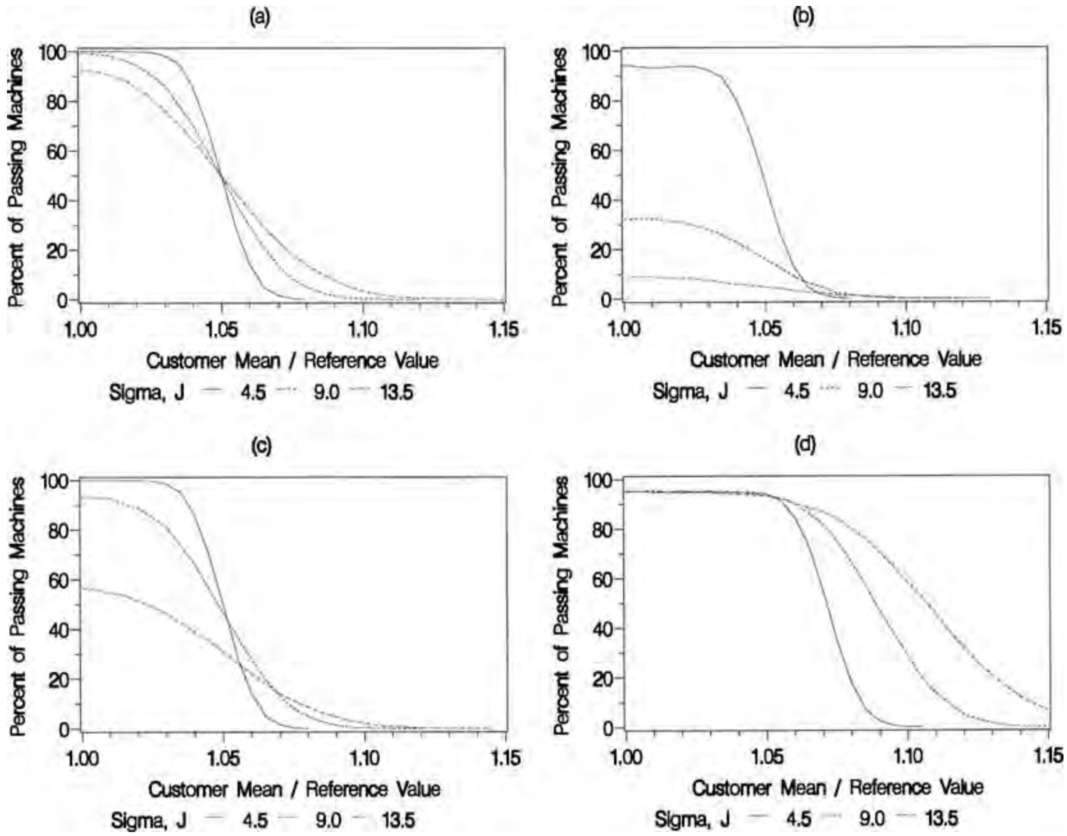

FIG. 9—*(a) Simulation results for the existing super-high energy ASTM rule. (b) Simulation results for the super-high energy ISO reference machine rule. (c) Simulation results for the super-high energy ASTM rule with relative range ≤15 %. (d) Simulation results for Wang's proposed super-high energy rule with D = 12 J.*

To examine passing rates for existing ASTM verification limits, machine capacities were discretized by rounding them to the nearest 50 J. Plots of passing rates versus rounded machine capacities are shown in Fig. 11. Machine capacities with less than ten passing machines were excluded from the plots. While there appears to be a slight upward trend in the data for each energy level, a linear fit of passing rate versus machine capacity did not produce any slopes that are significantly different from zero.

Country Analysis

We examined passing rates based on country affiliation. Because of the sensitive nature of revealing passing rates for each country, we divided countries into two groups, the United States and all others. Table

TABLE 5—*Passing rates for two pendulum types based on ASTM verification limits.*

Energy level	C type	U type	*P*-value
Low	2221 (89.4 %)	3889 (87.8 %)	0.02
High	2209 (89.0 %)	4056 (91.8 %)	<0.0001
Super-High	961 (91.7 %)	1219 (89.2 %)	0.02

TABLE 6—*P-values corresponding to hypothesis tests comparing means for two pendulum types based on an analysis of variance using machines passing the ASTM verification rules.*

Energy level	*P*-value
Low	0.005
High	0.001
Super-high	0.3

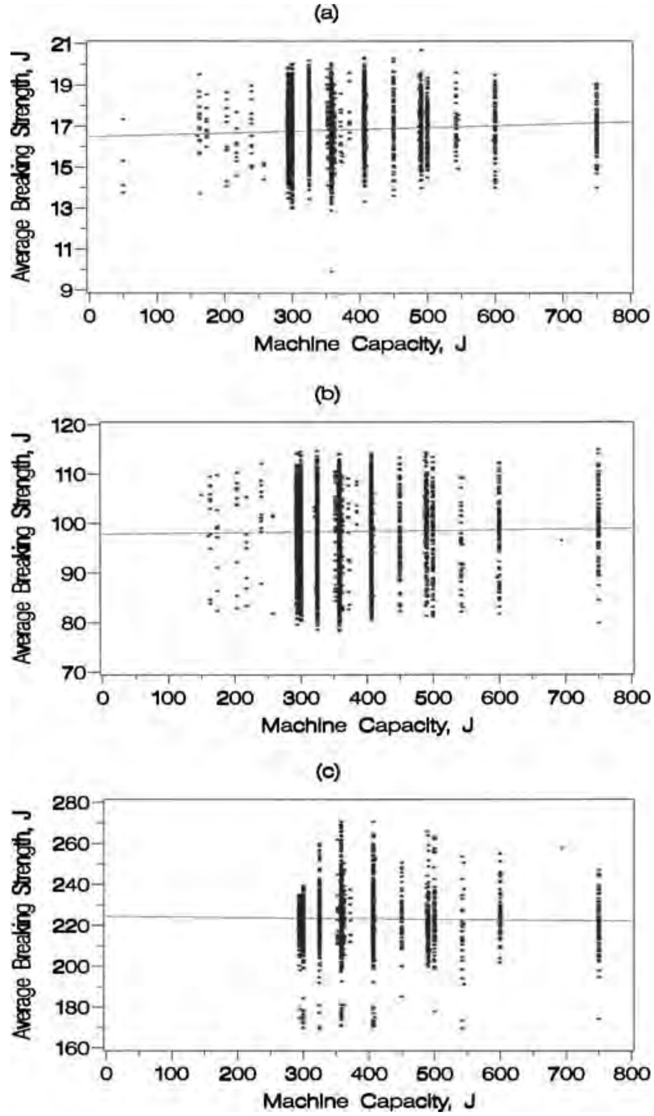

FIG. 10—*Customer averages versus machine capacity for (a) low energy, (b) high energy, and (c) super-high energy. The straight line fit to the data is represented by the line.*

8 displays passing rates for the two groups based on the existing ASTM verification rules at each energy level. A *P*-value associated with a test of equal proportions is also shown in Table 8.

Passing rates are about three percentage points higher for the United States than for all other countries for low and high energy levels. The super-high passing rate is slightly smaller for the United States than it is for all other countries, although there is no significant difference between the two rates.

Figure 12 displays passing rates based on existing ASTM verification rules for individual countries having more than ten passing machines. Country names have been removed from the plots. The data

TABLE 7—*Slopes, P-values (in parentheses), and correlation coefficients associated with lines fit to customer averages versus machine capacity for machines passing the existing ASTM verification rules.*

Energy level	Slope (*P*-value)	Correlation coefficient, r
Low	0.00090 (<0.0001)	0.06
High	0.0015 (0.2)	0.02
Super-high	−0.0028 (0.4)	0.02

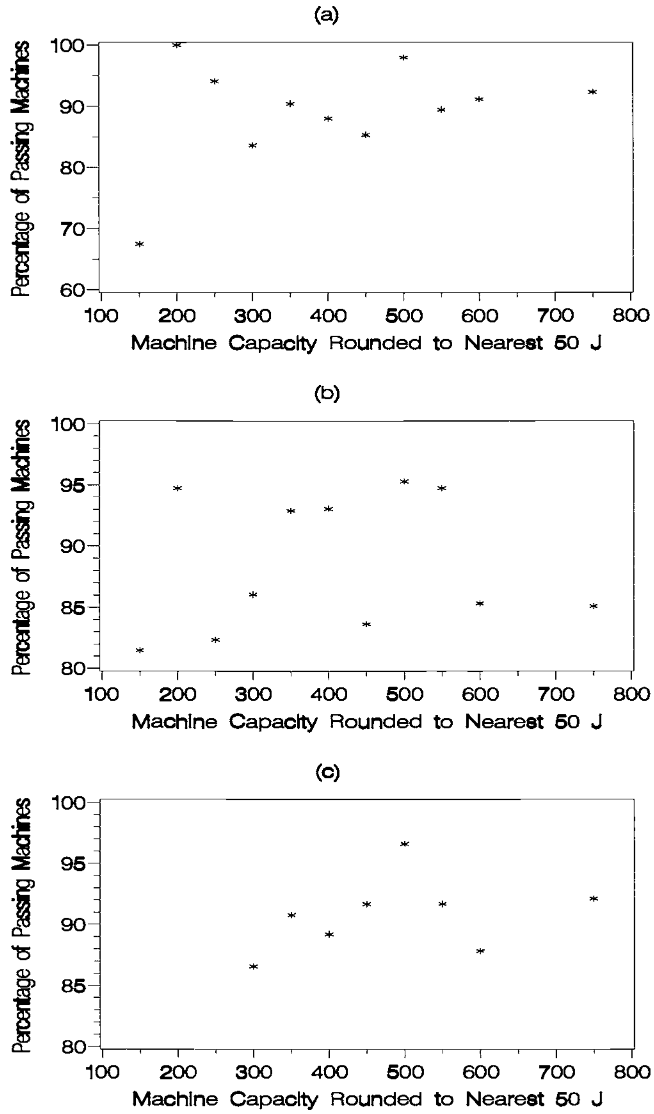

FIG. 11—*Percentage of machines passing the (a) low energy, (b) high energy, and (c) super-high energy ASTM verification limits versus machine capacity. Machine capacities with less than ten passing machines are not shown.*

indicate that ASTM passing rates for the United States are comparable to those of other countries at every energy level.

Discussion

The acceptable deviation of a customer mean from a reference value is not a quantity that can be determined through statistical means. It depends on the amount deemed appropriate based on engineering judgment. Through statistics, we can examine the properties of existing and proposed rules and provide information that can be used to make informed decisions.

The ASTM verification limits currently in use do not account for inherent specimen and system variation. Wang's rule accounts for this variation, but does not provide fixed limits for every lot of

TABLE 8—*ASTM passing rates for the United States and all other countries combined.*

Energy Level	United States	All other countries	*P*-value
Low	2649 (90.7 %)	3482 (86.7 %)	<0.0001
High	2686 (92.8 %)	3604 (89.5 %)	<0.0001
Super-high	758 (89.8 %)	1432 (90.6 %)	0.3

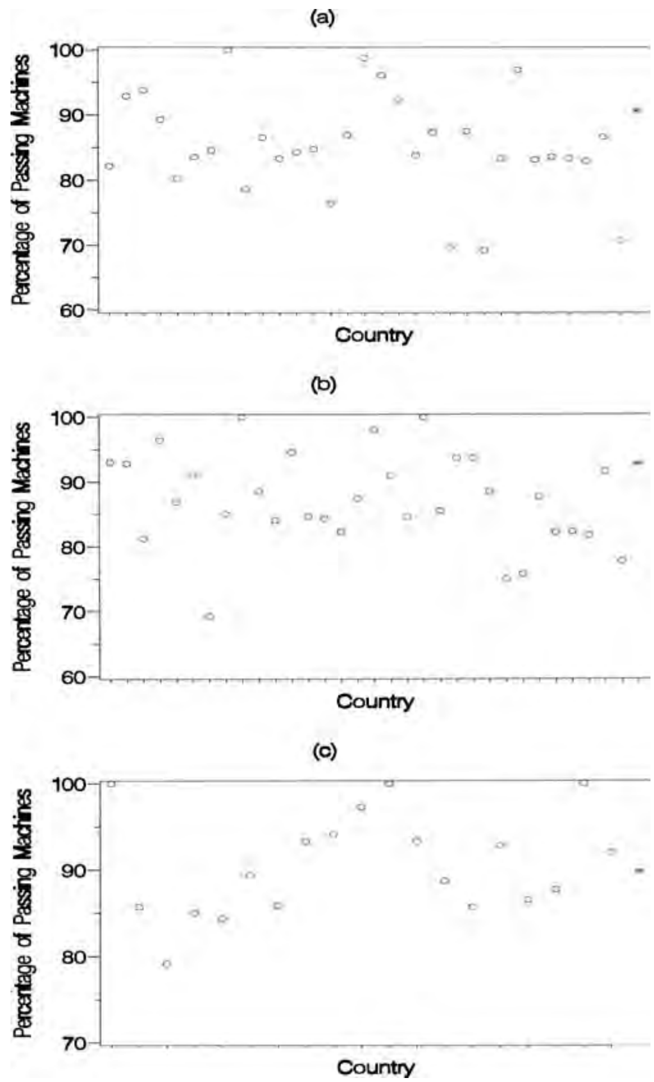

FIG. 12—*(a) low energy, (b) high energy, and (c) super-high energy ASTM passing rates by country. The United States appears as a star.*

specimens. Some participants in the Charpy program might be uncomfortable with limits that change depending on pilot lot variation since these limits could be wider than the current ASTM limits. Wang's rule is statistically justifiable, can be tailored to meet the needs of the program, and has a low probability of failing a "good" machine. Although Wang's rule is appealing from a statistical standpoint, it might not be the best solution in practice, especially for the super-high energy case. Typical customer variability at the super-high energy level is so large relative to pilot lot variability that most customers would fail the equality of variance test using Wang's rule. The large customer variability also brings into question the repeatability of customer measurements. Additional work is needed to understand and decrease customer variability.

We do not recommend increasing the current ASTM limits, unless this is done in combination with the addition of a range rule. Widening any existing limits without accounting for variation would only serve to increase the potential for large differences between the customer's average and the true unknown breaking strength of the material. In particular, increasing the existing Low energy ASTM limit to 4 J, without implementing a range rule as well, would completely undermine the program objectives since virtually all machines would pass.

Determining appropriate rules to limit variation via range and relative range rules is a good way to improve the ASTM program, and limiting customer ranges based on the 95th percentile of the range distribution appears to be a reasonable approach. Since ASTM A and ASTM B rules can be adjusted so that they produce nearly identical passing rates, we really only need to determine a single rule that can be expressed in absolute units or on a percentage basis. If, for example, a range rule based on the 95th percentile were proposed to accompany a 2 J or 5 % energy rule, we might achieve a reasonable compromise between ASTM and ISO rules that could satisfy both organizations. Based on low energy historical data, a 2 J energy limit with a 95th percentile range rule (3.5 J) would have a 90.7 % passing rate.

We examined the passing rates and distributions of means for C and U type pendulums. Although we found statistically significant differences between passing rates for the two groups, it is unclear whether the differences are of practical significance. Also, we discovered dependence between pendulum type and lot which merits further study.

Analyses of machine capacity did not reveal any significant relationships between passing rates and machine capacity. We also determined that there is no convincing evidence that average impact energy is increasing or decreasing as machine capacity increases. While there are slight trends in average impact energies for the low energy level, more work is needed to verify that the trend is significant.

Passing rates based on existing ASTM verification rules indicate that machines in the United States are comparable to machines in other countries for all energy levels. Low and high energy passing rates are about 3 % higher for the United States than for all other countries.

Acknowledgments

The authors thank Jack Wang of NIST and Cathy Dewald of NIST for their valuable assistance during the preparation of this document. This work is a contribution of the National Institute of Standards and Technology and is not subject to copyright in the United States.

Appendix A

In the ASTM verification program, the pooled standard deviation of the pilot lot (S_P) is computed as

$$S_P = \sqrt{\frac{(n_1 - 1)s_1^2 + (n_2 - 1)s_2^2 + (n_3 - 1)s_3^2}{n_1 + n_2 + n_3 - 3}}, \tag{A1}$$

where n_1, n_2, n_3 are the number of verification specimens tested on each of the three master machines, and s_1, s_2, s_3 are the associated standard deviations. Typically, 25 verification specimens are tested on each machine.

Appendix B

The F test is used to determine the equality of two sample variances. For our problem, we are only concerned if the customer's sample variance (S_C^2) is large compared to the pooled pilot lot variance (S_P^2). If the ratio

$$F = \frac{S_C^2}{S_P^2} \tag{A2}$$

is greater than the 100(1-α)th percentile of the F distribution, denoted by $F_{1-\alpha;4,72}$, then we would conclude that S_C^2 is significantly larger than S_P^2. The quantities 4 and 72 correspond to the degrees of freedom for the customer and pooled pilot lot variances, respectively, and α is the significance level of the test (usually 0.05). See [6] for more information regarding equality of variance tests.

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Journal of ASTM International, October 2005, Vol. 2, No. 9
Paper ID JAI12872
Available online at www.astm.org

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Reference Impact Specimens Made from Low Carbon Steel: Report on Production and Use

ABSTRACT: This paper describes a method of producing reference specimens from low carbon steel and reports the results of a national proficiency testing by 45 laboratories. The reference impact specimens of low carbon steel are much cheaper than the traditional ones, and the proficiency testing proved that the specimens are valid for finding out the problems of impact machines. Furthermore, the data showed that an impact machine would represent the similar relative bias at a different energy level of reference specimen, so it is sufficient to use reference specimens with one absorbed energy level to verify impact machines annually.

KEYWORDS: Charpy verification specimen, impact test, reference material

Introduction

The notched bar impact test is one of the most important test methods for the acceptance test of metallic materials. It is used to verify whether the materials have enough impact toughness at the test temperature. In most cases, it is essential to test the materials which are not in the brittle state at a predefined temperature. During a material acceptance test, the suitability of pendulum impact machine is usually based on the direct verification which calibrates its scale, the specified dimensions, the mass of the pendulum and readings, etc. However, when using the direct verification, it is found that sometimes two machines, both of which met all the requirements such as the specified dimensions, mass of the pendulum, and readings, give significantly different values when the specimens from the same material are tested. To avoid these discrepancies, certain standards, such as ASTM E 23 and ISO 148-2, require an annual verification of Charpy impact machines using reference specimens as an indirect verification.

While indirect verification can increase the reliability of impact test results, it is not widely used for economic reasons. Usually 15 reference specimens are needed each time to perform indirect verification for an impact machine. A normal reference impact specimen is made of 4340 steel with the same dimension of 55 × 10 × 10 mm [1–3]. To obtain a different absorbed energy level, the specimen needs to be treated with a different heat process. This means some energy level specimens are impacted in a transition temperature zone of the steel. As the absorbed energy of the steel distributes in a much larger area in transition temperature zone than that in ductile zone, the manufacturer has to limit the utilization of the steel with ultra pure and ultra uniform characters to reduce the dispersion of the reference specimen values (Fig. 1) [4]. As a result, the indirect verification method is too expensive to be practiced widely.

Thus, a method that could make cheaper impact reference specimens and reduce the number of the specimens to verify an impact machine annually is desirable.

Manuscript received 9 October 2004; accepted for publication 15 March 2005; published October 2005. Presented at ASTM Symposium on Pendulum Impact Machines: Procedures and Specimens on 8 November 2004 in Washington, DC.
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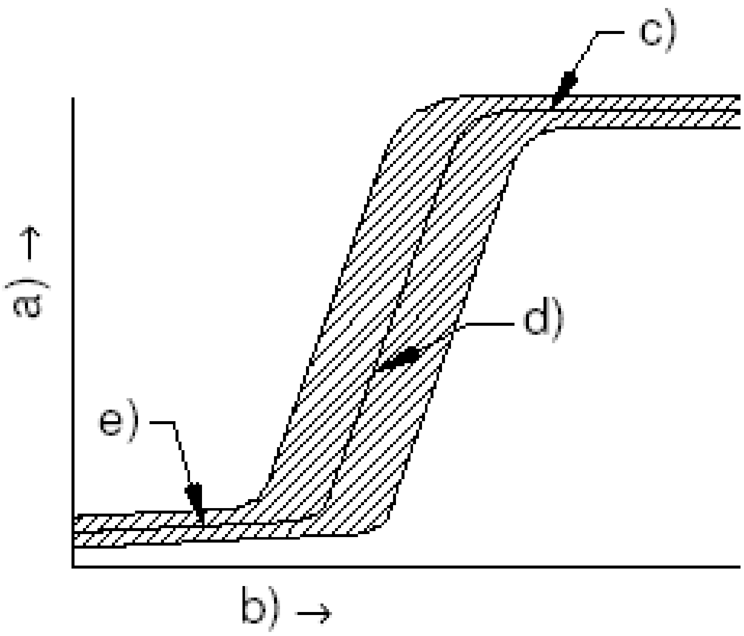
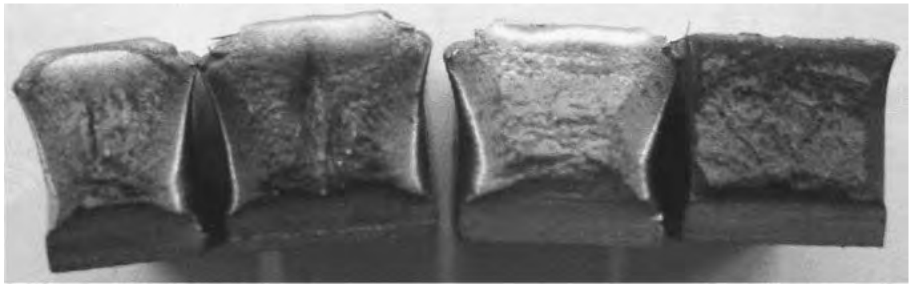


FIG. 1—*Schematic diagram of the steel energy absorbed-temperature curve:* a*) absorbed energy,* b*) temperature,* c*) upper shelf zone,* d*) transition zone,* e*) lower shelf zone.*

The Method of Making Cheaper Reference Impact Specimens

For the new method it is essential to use low carbon steel to make Charpy V-notch reference specimens in the upper shelf zone, instead of using the 4340 steel in the transition zone and the upper shelf zone. By doing this, the absorbed energy dispersion of specimen can be significantly reduced. Furthermore, it is performed with very small uncertainty on impact energy. To obtain uniform morphology in metallographic, the steel with less than 0.09 % carbon is used. Thus, the segregation in the steel can be minimized, and the steel plates related to the uniform parts of temperature during the production process are selected as raw materials. Finally, the reference specimens are taken from the longitudinal direction. To get different absorbed energy levels, different cross-sections of specimens have been chosen. The size of the specimen may not be the same as the one defined by ASTM E 1271, but the distance between the striking center and the center of the percussion in the specimen may still comply with the requirement on paragraph A2.3.7 of ASTM E 23. The detailed information on making the new reference impact specimens can be found in Ref. [5].

The standard deviation of the absorbed energy values of reference impact specimens must be less than 5 % according to ISO 148-3 requirement. For the broken specimens with two fracture surfaces after impacting, it is difficult to keep the standard deviation in such a narrow range because there are too many changes regarding the cleavage fracture surface area in the transition zone. There are different cracks perpendicular to fracture surfaces of specimens impacted in the upper shelf zone (see Fig. 2). In other words, the low carbon steel impact specimens absorb the energy mainly by bending deformation when impacted at the ambient temperature (Fig. 3). The absorbed energy depends mainly on the strength of the material and the deformation of the specimen. Since the ratio of standard deviation to average of absorbed energy is lower in the impact specimens made from low carbon steel than that from 4340 steel, the standard deviation of the absorbed energy of the low carbon steel impact specimens can be reduced to less than 5 %.



(a) (b) (c) (d)

FIG. 2—*Fracture surfaces of impact shown schematically:*
(a) two cracks perpendicular to the fracture surface of specimen impacted in upper shelf zone.
(b) one crack perpendicular to the fracture surface of specimen impacted in the upper shelf zone.
(c) less cleavage fracture surface of specimen impacted in transition zone.
(d) more cleavage fracture surface of specimen impacted in transition zone.

FIG. 3—*The low carbon steel impact specimen impacted shown schematically.*

The Status and the Results of National Proficiency Testing with 45 Laboratories

China National Accreditation Board for Laboratories (CNAL) organized 45 laboratories to perform an impact national proficiency test with the new reference impact specimens of low carbon steel in 2002. Every laboratory received three specimens with 5 × 10 × 55 mm dimensions and three specimens with 7.5 × 10 × 55 mm size. The tests were performed at ambient temperature. The results are shown in Fig. 4 [6]. In the figure, 5avg is the set average value of three specimens with 5 mm width in one laboratory; 5R is the range value of the set of three specimens with 5 mm width in one lab. 7.5avg is the set average value of three specimens with 7.5 mm width in one laboratory; 7.5R is the range value of the set of three specimens with 7.5 mm width in one laboratory. The results showed the difference of the absorbed energy measured by different laboratories may be much larger than the requirement of the standard ISO 148-2. It suggested that although these laboratories had passed the direct verification, the impact results may not meet the standards of ISO 148-2, and it is reasonable to require an indirect verification on the impact machines annually. In order to determine the reasons for such variation among different laboratories, the experts of CNAL checked some of laboratories which got unreasonable results and identified the main problems:

1. There are problems with the specimen support or anvil, it cannot deliver the impact to the specimen at the right direction, and the results are higher than normal.
2. The specimen is not put on the central position before impacting, and the results are lower than normal.
3. The distance between anvils is larger than that required, and the results are smaller than the normal one. In addition, experts also found out some other problems in some laboratories. For example, some specimen surface metal was scraped off, and there is a gap between the specimen supports and the anvils. The fact that so many problems can be found out shows the low carbon steel reference impact specimens are valid in the indirect verification.

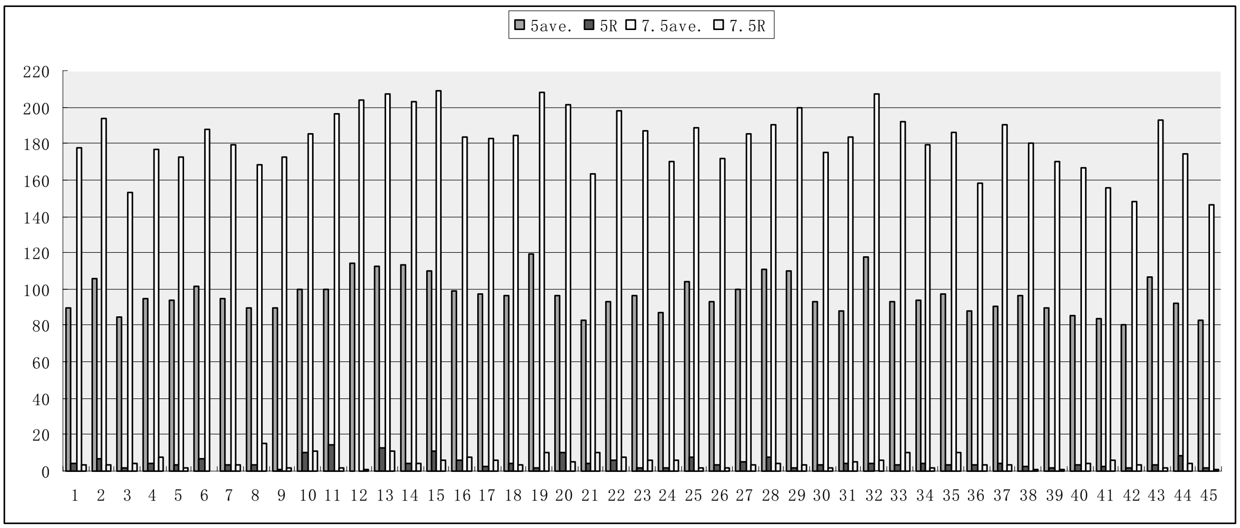


FIG. 4—*The results of proficiency test with 45 laboratories.*

According to the results obtained from 45 laboratories, some interesting data could be calculated: for 5 × 10 × 55 mm specimens, the average impact energy value of three specimens set within 45 laboratories is 96.9 J, median is 95.1 J, maximum is 119.3 J, and minimum is 80.0 J; the average range values of each set of three specimens within 45 laboratories is 4.5 J; and the average standard deviation of each group of three specimens is 2.69 J. And for 7.5 × 10 × 55 mm specimens, the average impact energy value of three specimens set within 45 laboratories is 182.4 J, median is 184.3 J, maximum is 208.7 J, and minimum is 146.3 J; the average range of values of each set of three specimens within 45 laboratories is 4.8 J; and the average standard deviation of each set of three specimens is 2.84 J. The data show that the standard deviation of the low carbon steel impact specimens is much lower than the standard ISO-148-3 requirement limit, with a lower uncertainty for verification.

The Strategies to Reduce Number of Reference Specimens for Annual Verification

Laboratory results should be reanalyzed: divide the average value of three specimens for each laboratory by the median value of 45 laboratories to obtain relative values. Then, use the relative values for specimens with the size of 5 × 10 × 55 mm and for specimens with 7.5 × 10 × 55 mm size to draw a scatter pattern as in Fig. 5. It shows that the relative values of the different impact energy levels are closed to a line of y = x in Fig. 5. The Pearson correlation coefficient r is as high as 0.868. Figure 5 and the r-value denote that an impact machine with bias will represent similar relative bias by different energy level reference specimens. So it is possible to use one absorbed energy level reference specimen instead of two or three energy level reference specimens to verify impact machine annually.

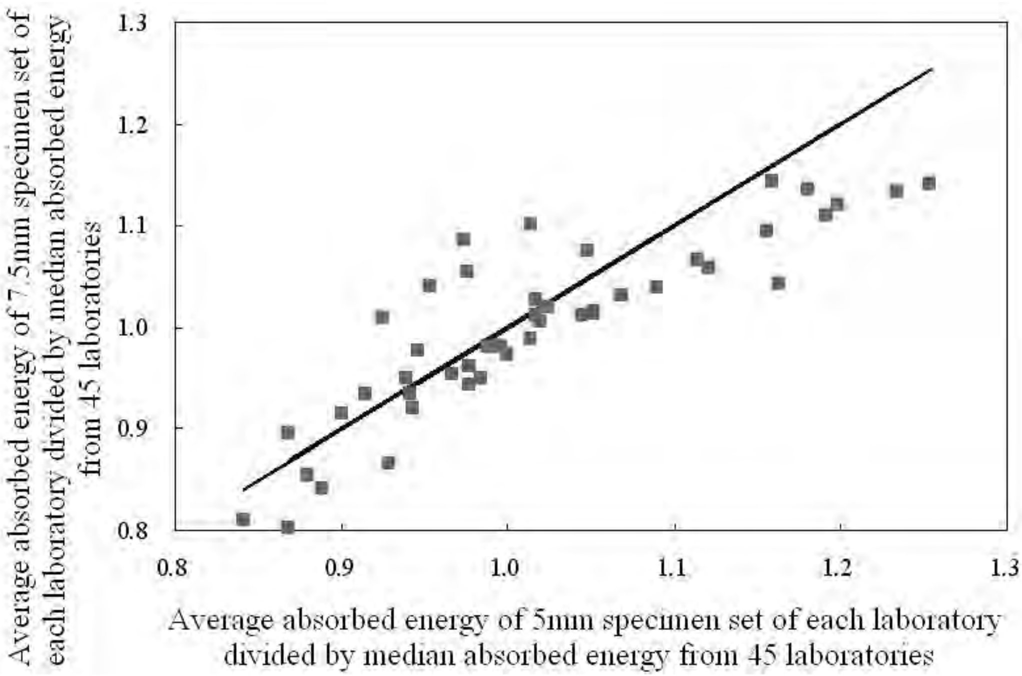


FIG. 5—*Scatter graphics on absorbed energy ratio of 5 and 7.5 mm width specimens.*

Conclusions

The annual indirect verification is needed to guarantee the capability of the impact machine to get reasonable results. The strategies of reducing the cost of the indirect verification can be briefly described as follows:

a. Use low carbon steel instead of ultra pure and ultra uniform alloy steel to make the reference impact specimen.
b. Use one instead of three or two absorbed energy level reference specimens in annual indirect verification.
c. Use two instead of five reference specimens set since the standard deviation is very low.

By these three strategies, the cost of indirect verification could be reduced from more than $300 to less than $10.

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Journal of ASTM International, July/August 2005, Vol. 2, No. 7
Paper ID JAI12873
Available online at www.astm.org

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Impact Characterization of Sub-Size Charpy V-Notch Specimens Prepared from Full-Size Certified Reference Charpy V-Notch Test Pieces

ABSTRACT: To investigate the feasibility of the production of sub-size Charpy reference test pieces, tests were performed on sub-size samples (3 × 4 × 27 mm³) carefully machined from full-size (10 × 10 × 55 mm³) Charpy V-notch certified reference test pieces. The measured absorbed energy (KV) values indicate a highly satisfactory homogeneity of the sub-size specimens. Sub-size specimens were prepared from full-size reference test pieces of 30, 60, 80, 120, and 150 J nominal absorbed energy; and values between 2 J and 7.2 J were obtained, covering almost fully the range of interest for sub-size Charpy tests. A linear relationship is observed between the KV values of sub-size and full-size samples of the same material.

KEYWORDS: sub-size Charpy specimens, certified reference material, absorbed energy

Introduction

Direct and Indirect Verification of Full-Size Charpy Impact Test Machines

The impact resistance of metallic materials is commonly tested using pendulum impact tests. The principles of this test were first published in 1898 in the U.S. [1] and in 1901 in France [2]. Throughout the 20th century, the test has become more reliable, largely as a result of the acceptance of more standardized test procedures.

The standard procedures – whether ISO, EN, ASTM, or JIS – basically address three main issues. One issue is the shape of the sample. The full-size (10 × 10 × 55 mm³) V-notched test piece nowadays is the most used geometry. With careful machining, one readily meets the tolerances specified in the standards, as can be easily verified with a profile projector or equivalent measuring system. A second issue is the structure of the pendulum. The assessment of the compliance of the pendulum with the constructional specifications laid out in the standards is the so-called "direct verification." Direct verification is relatively straightforward for a trained and experienced person having suitable and calibrated tools. However, direct verification does not assess the dynamic performance of the pendulum, i.e., its behavior during the impact test. Also, the direct verification requires full access to the pendulum, which is a problem in the case of pendulums installed in 'hot cells' (special laboratory areas where irradiated or contaminated specimens are handled and tested).

Manuscript received 15 November 2004; accepted for publication 10 January 2005; published July 2005. Presented at ASTM Symposium on Pendulum Impact Machines: Procedures and Specimens on 8 November 2004 in Washington, DC.

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The third issue tackled in the standard procedures is the "indirect verification" of the pendulum performance. The indirect verification consists of breaking a set of five reference test pieces. For a pendulum to pass the indirect verification, the average energy absorbed by the five test pieces, as well as the variation, need to meet particular criteria. Reference test pieces for the indirect verification of Charpy impact pendulum test machines can be obtained from a number of Certified Reference Materials producers, one of which is the Institute for Reference Materials and Measurements, Joint Research Centre of the European Commission (IRMM) in Geel (Belgium). A few years ago, IRMM took over the reference material certification activities formerly managed by the EC Community Bureau of Reference (BCR). The Charpy V-notch certified reference test pieces, formerly known as BCR samples, are currently available as ERM-materials. ERM is the brand name of certified reference materials produced by the European Reference Materials consortium [currently IRMM (EC), BAM (DE), and LGC (UK)].

Sub-Size Charpy Impact Tests

Charpy impact tests on sub-size specimens (smaller than full-size) are commonly performed in order to investigate local aging, irradiation, or other damage effects, whenever there is a limited amount of material available, or, in the case of irradiation studies, when space is limited inside irradiation facilities. In Europe, the most popular sub-size Charpy geometry is the KLST (*Kleinstprobe*) specimen, originally derived from a German standard [3], whose nominal dimensions are shown in Fig. 1.

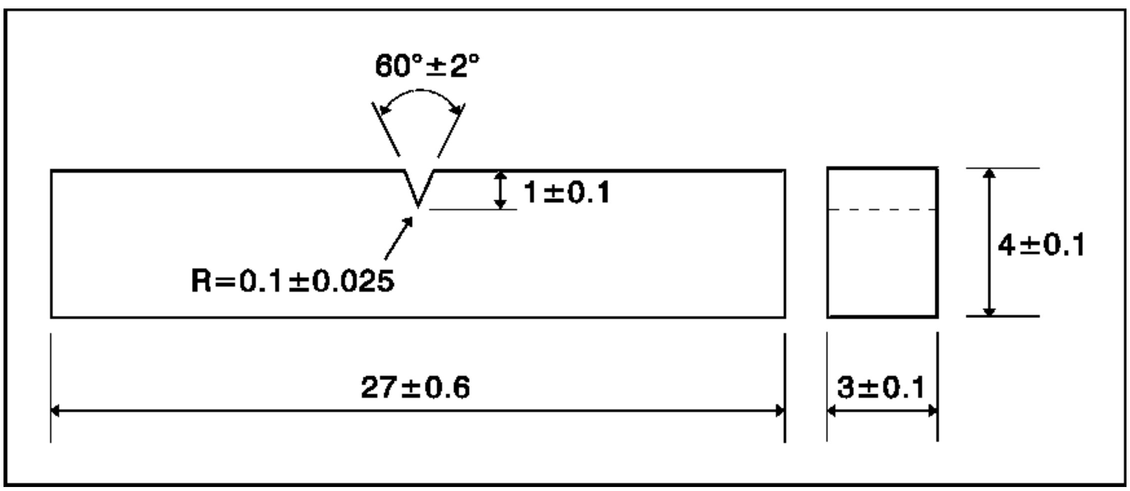

FIG. 1—*Sub-size specimen of the KLST type used in this investigation (dimensions in mm).*

Sub-size Charpy specimens are normally tested using small-scale pendulums with reduced impact capacity and reduced anvil spacing, (approximately) scaled to the sub-size sample dimensions. Such machines cannot be verified with full-size Charpy reference test pieces. To the authors' knowledge, no certified sub-size reference test pieces are currently available; therefore, sub-size Charpy impact test set-ups cannot be verified against ISO-148-2. ASTM E 2248-02 describes a verification procedure involving sub-size samples prepared from "a material with a microstructure that produces small scatter in the results," but the production of these specimens is left to the pendulum owner. The lack of certified sub-size reference test pieces is especially problematic for machines in controlled areas ("hot cells"), where direct verification of the pendulum is quite difficult.

Given the increased use of instrumented and sub-size pendulums, the authors consider it worth investigating whether there are cost-effective means of providing the impact community with reference test pieces either of different (sub-)size or with certified rupture strength or force-displacement characteristics. This paper focuses on the issue of sub-size test pieces.

Materials

The certified reference test pieces used in this work have been prepared from two different types of steel. These steels and the heat treatments imposed on them were selected to obtain KV-values within particular ranges. The four lower energy batches (nominal KV = 30 J, 60 J, 80 J, and 120 J) are prepared from AISI 4340 steel. The higher energy level (nominal KV = 160 J) is made from ASTM 565 grade XM32 steel.

Reference test pieces are produced batch-wise: test pieces from a single batch have undergone their heat treatment together. At the time of production, heat treatment was performed in salt baths. Single batches consisted of about 750 samples, which was the maximum amount of samples that could be heat treated together. The steel was supplied as hot-rolled bars. The required 750 samples were obtained from a limited number of steel bars, which were cut into rectangular beams of 58 mm length. Prior to heat treatment, these beams were machined to 55 mm length and 11 mm × 11 mm cross-section.

The first heat treatment step was an austenization treatment (840°C for AISI 4340 steel, 1040°C for ASTM 565). From this bath, samples were quenched in oil at 40–45°C. After the oil-quench, the samples were annealed in a second salt bath at a temperature selected in order to obtain the desired KV-level. After the annealing treatment, samples were cooled down in air and machined to the test piece dimensions imposed in EN 10045-2. First, the cross-section was reduced to 10×10 mm², respecting the orthogonality of the four long faces of the bar. Then the surface was finished to roughness Ra < 0.8 µm. Finally, the V-notch was introduced using a diamond grinding tool with the appropriate V-profile. Samples were cleaned and packed in sets of five, in oil-filled plastic bags.

The certified values of the batches of reference test pieces were determined based on a comparison of 30 samples of the batch to be certified with 25 samples of the so-called Master Batch with the same nominal absorbed energy [4]. The certified absorbed energy of the Master Batches was previously determined in a certification exercise involving an international comparison among approximately ten laboratories. After production, the reference test pieces were stored at 18°C at IRMM.

Experimental Procedure

Sub-Size Sample Preparation

A first series of sub-size samples of the KLST type was machined from broken full-size certified reference test pieces, previously tested for the indirect verification of a 300 J pendulum. Four KLSTs can be obtained from one BCR half-specimen as shown in Fig. 2. Samples were prepared from one half sample of each available nominal energy level (30 J, 60 J, 80 J, 120 J, and 160 J), resulting in a total of 20 KLST samples. Since these specimens came from broken full-size Charpy halves, the relevant deformed region adjacent to the fracture surface had to be cut off first. Therefore, the resulting sub-size test pieces were slightly shorter than the nominal KLST length: the measured length was approximately 26.5 mm rather than 27 mm. Since for a

Charpy sample the length is known to be a much less critical dimension than width, thickness or notch configuration, such deviations were expected to have a negligible effect on the test results. To investigate this assumption, a second series of KLST specimens was machined from unbroken certified reference test pieces. In this case, eight sub-size pieces were machined for each energy level, for a total of 40 samples.

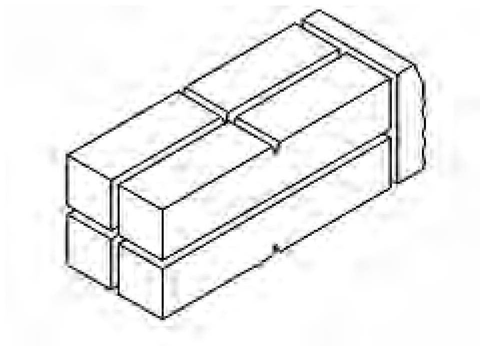

FIG. 2—*Extraction of four KLST specimens from a broken full-size specimen half.*

Sub-Size Charpy Impact Tests

All sub-size specimens (20 from the first series and 40 from the second series) were tested according to the ESIS TC5 Draft Test Procedure [5] at room temperature, using a small-scale CEAST pendulum impact tester located in the Mechanical Testing Laboratory of SCK•CEN in Mol (Belgium). The capacity of the pendulum was 15 J and the speed at impact 3.71 m/s. Absorbed energy values ($KV_{s\text{-}s}$) were recorded from the machine dial energy indicator and were corrected for energy losses due to friction and windage.

Test Results

Tests on Sub-Size Samples Extracted from Broken Full-Size Reference Test Pieces

In the case of KLST specimens extracted from broken certified reference samples, not only is the certified absorbed energy value KV_{cert} of the original sample known (from the certificates supplied with the reference materials), but the actual result (KV_{exp}) of the test on the full-size sample is also known. The results from this first series of tests are given in Table 1, which also includes: the relative expanded uncertainty U_{rel} (at the 95 % confidence level) corresponding to KV_{cert}, the average value of $KV_{s\text{-}s}$ for each data set with its relative standard deviation (RSD), and the ratio between KV_{exp} and $KV_{s\text{-}s}$ for each energy level.

An interesting observation is related to the standard deviation of the results obtained on the sub-size test pieces. Although the number of sub-size test pieces (4) is too small to reliably assess at each level the standard deviation, it is significant that at each of the five tested energy levels, the parameter is found to be less than 2.5 %. This is approximately the average homogeneity of the batches of full-size certified reference test pieces produced by IRMM over the last five years. This indicates that the decrease of the volume around the notch tip sampled by the impact test does not conflict with the homogeneity of the steel microstructure. One can therefore consider that the steel microstructure is sufficiently homogeneous to reduce the ‘sample-intake’ to the KLST sub-size geometry.

TABLE 1—*Results of the impact tests on sub-size Charpy specimens prepared from broken full-size samples. KV_{s-s} values (average and standard deviation) are calculated over data sets of four tests.*

"PARENT" REFERENCE SPECIMEN				SUB-SIZE SPECIMENS		Ratio KV_{exp}/KV_{s-s}
Nominal energy level	KV_{cert}, J	U_{rel}, %	KV_{exp}, J	KV_{s-s}, J	RSD, %	
30 J	24.3	4.5	23.7	1.87	2.4	12.7
60 J	58.2	3.4	56.6	3.27	1.2	17.3
80 J	77.6	3.0	76.0	4.11	1.8	18.5
120 J	123.3	4.3	121.8	5.76	1.1	21.1
160 J	153.9	2.8	155.2	7.18	2.1	21.6

Absorbed energy values KV_{s-s} are shown in Fig. 3 as a function of KV_{exp} of the "parent" sample. A clearly linear relationship is observed ($R^2 = 0.9988$). Given the good correlation between certified and experimentally measured KV values, it is equally meaningful to relate the energy of the sub-size specimen (KV_{s-s}) to the certified energy of its "parent" reference sample (KV_{cert}) ($R^2 = 0.9986$).

We also observe that KV_{s-s} values cover quite evenly a significant portion of the typical energy range encountered in such tests for commercially available steels (up to 10 J). In fact, the result of the highest energy level (7.18 J) corresponds to a higher fraction (72 %) of the expected maximum energy (10 J) than for conventional reference samples, where 160 J corresponds to only 64 % of the typical energy range (up to 250 J). In other words, sub-size reference specimens seem to offer a slightly better "coverage" of the energy range of a typical impact test than currently available ERM certified reference test pieces.

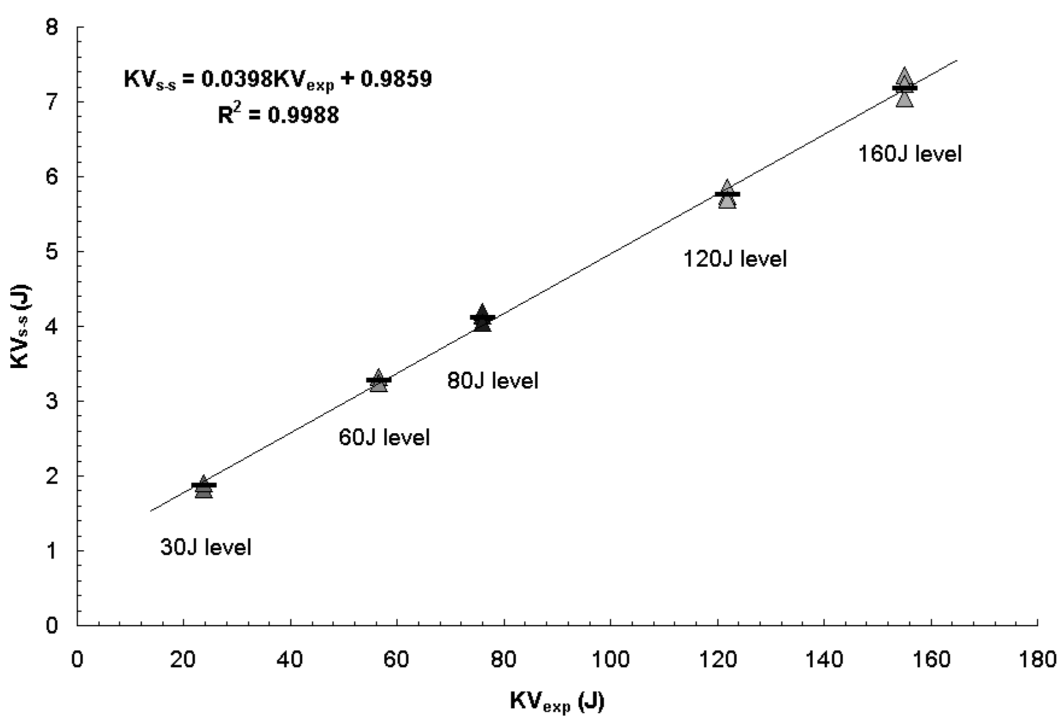

FIG. 3—*Relationship between KV_{s-s} and KV_{exp} for the sub-size samples prepared from broken full-size specimens. Thick short lines indicate average values within energy levels.*

The ratio $KV_{exp}/KV_{s\text{-}s}$ (Fig. 4) does not remain constant, but increases with increasing absorbed energy and seemingly approaches a plateau for KV_{BCR} greater than 120 J. This circumstance is probably related to the change of the ratio of plastic zone size versus test piece size. Additional analyses would be required to substantiate this statement.

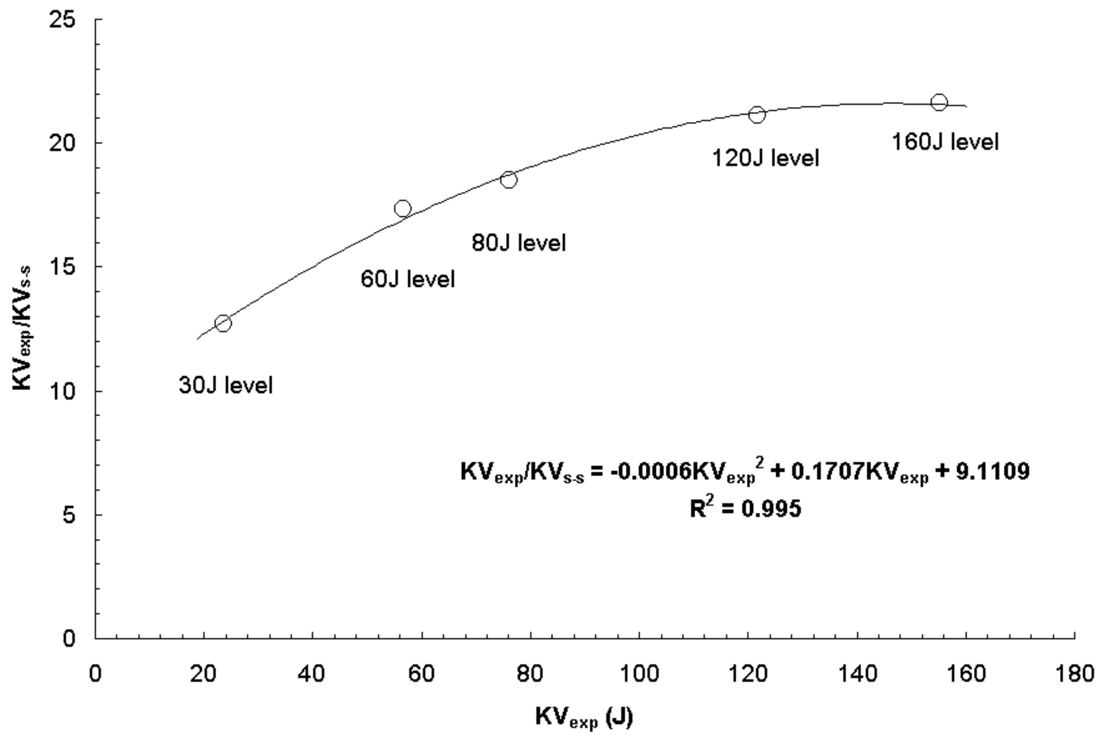

FIG. 4—*Ratio between energies absorbed by full-size and sub-size specimens prepared from broken full-size specimens.*

Tests on Sub-Size Samples Extracted from Unbroken Full-Size Reference Test Pieces

The second series of samples (eight test pieces per energy level) was tested under identical conditions. In this case, reference can only made to the nominal energy values (KV_{cert}) given in the BCR-certificates of the batches from which the "parent" sample originated. Results are summarized in Table 2.

TABLE 2—*Results of impact tests on sub-size Charpy specimens prepared from unbroken full-size samples. $KV_{s\text{-}s}$ values (average and standard deviation) are calculated over data sets of eight tests.*

"PARENT" REFERENCE SPECIMEN			SUB-SIZE SPECIMENS		Ratio
Nominal energy level	KV_{cert}, J	U_{rel}, %	$KV_{s\text{-}s}$, J	RSD, %	$KV_{cert}/KV_{s\text{-}s}$
30 J	24.3	4.5	1.97	2.1	12.3
60 J	58.7	2.6	3.40	1.4	17.3
80 J	77.6	3.0	4.16	2.2	18.7
120 J	121.2	4.6	5.59	2.8	21.7
160 J	159.0	3.9	7.41	1.6	21.5

Again, the standard deviations of the results obtained from the sub-size test pieces are comparable to the homogeneity of the batches of certified reference test pieces (Table 2). Results thoroughly consistent to the first series are also shown in Figs. 5 and 6, demonstrating that the shorter length of the test pieces from the first test series has a negligible influence.

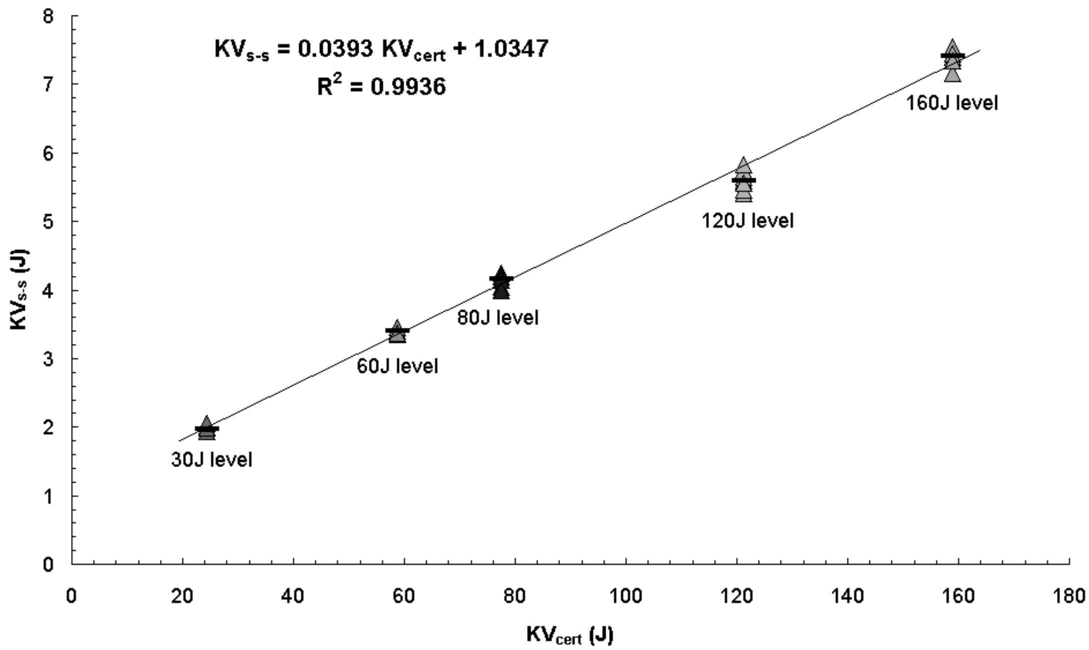

FIG. 5—*Relationship between $KV_{s\text{-}s}$ and KV_{BCR} for sub-size specimens prepared from unbroken full-size samples. Thick short lines indicate average values within energy levels.*

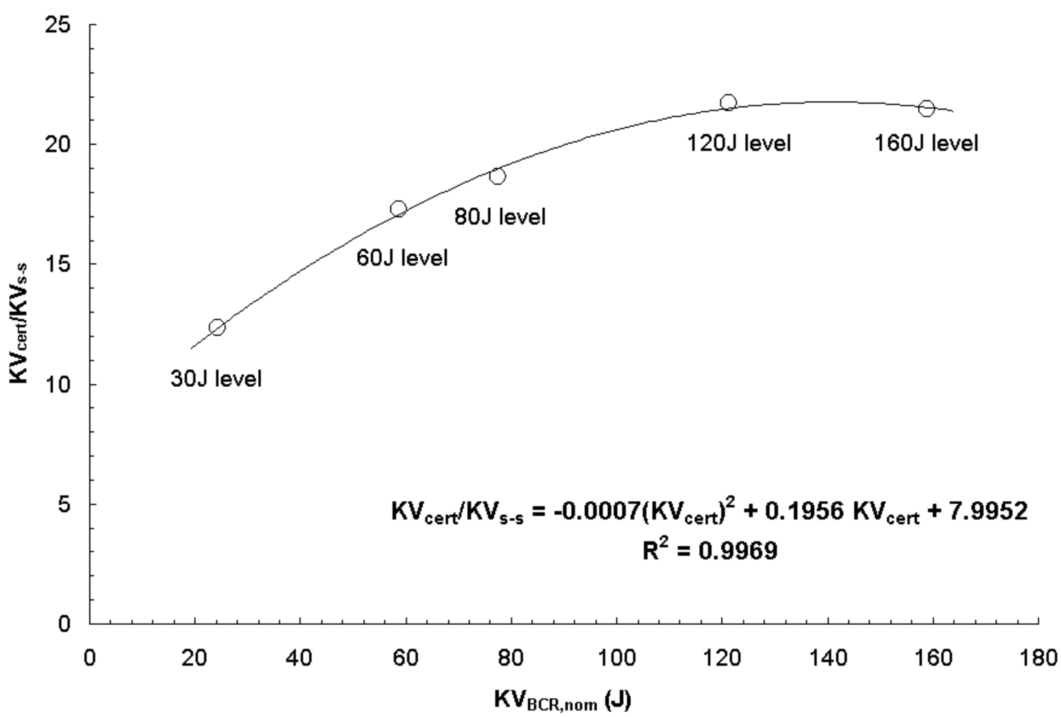

FIG. 6—*Ratio between energies absorbed by full-size and sub-size specimens prepared from unbroken full-size samples.*

Roadmap to the Production of Sub-Size Reference Charpy Specimens

The results shown above indicate that the production of sub-size reference test pieces is likely to be successful. For a Certified Reference Material producer to succeed in such a certification project, a number of additional conditions must be met. At first, the intended use of the reference test pieces must be clearly defined. Here, one could readily refer to the ISO 148-2 standard procedure about the verification of Charpy impact test machines. However, agreement must first be reached on the verification ranges allowed for sub-size impact tests, as this is currently the most debated issue in the full-size area. On the other hand, the required amount of samples needs to be estimated. The main obstacle here seems to be the broad range of sub-size geometries that are being used throughout the world. Standardization of the test piece would inevitably increase the size of the market and reduce the cost per set of test pieces to a level acceptable for the user.

In the actual production a number of approaches can be followed. The certified value of a batch of reference test pieces can be determined in an international intercomparison between a number of selected test laboratories with the required metrological expertise. This is an expensive route and delivers limited numbers of samples. Alternatively, as is done for the full-size Charpy test pieces at IRMM, such batch tested in an international intercomparison could be treated as a Master Batch. Secondary batches then could be produced by performing tests on a dedicated single pendulum under repeatability conditions, comparing Master Batch and secondary batch specimens.

However, from the cost-effective point of view, the results of this paper seem to offer an interesting third option. This would consist of preparing sub-size reference test pieces from previously certified full-size reference test pieces. This approach would avoid the need for a Master Batch of sub-size reference test pieces, or that of a set of dedicated reference sub-size pendulums. The only costs would relate to the full-size reference test pieces, the machining of the sub-size test pieces, and the performance of tests on a number of sub-size reference test pieces to determine their homogeneity. Obviously, for such a pragmatic approach to find acceptance, the results in this paper would need to be confirmed. In particular, the relation between the full-size and sub-size test piece absorbed energies needs to be determined quantitatively with sufficient reliability.

Conclusions

The absorbed energies of 60 test pieces of the KLST-type ($3 \times 4 \times 27$ mm^3), extracted from full-size reference test pieces (of energy levels between 30 J and 160 J), were measured at room temperature according to the ESIS TC5 Draft Test Procedure. The measured energies cover a range from 2 J to 7.4 J, corresponding to a representative share of the energy range commonly encountered in impact tests on KLST specimens (up to 10 J).

Data scatter appears of the same magnitude as the homogeneity of the batches of full-size certified reference test pieces. This indicates that the steel microstructure is sufficiently homogeneous to reduce the test pieces size from full- to sub-size geometries. Standard mechanical workshop tolerances provide acceptable homogeneity results. Even test pieces slightly shorter than the nominal length do not exhibit appreciable deviations.

In summary, the study presented here demonstrates the feasibility of producing sub-size reference Charpy specimens, using the same materials and production routes as for the standard, commercially available certified reference test pieces.

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SESSION IV: ISSUES WITH INSTRUMENTED STRIKERS

Journal of ASTM International, March 2006, Vol. 3, No. 3
Paper ID JAI12876
Available online at www.astm.org

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Different Approaches for the Verification of Force Values Measured with Instrumented Charpy Strikers

ABSTRACT: The Charpy test plays a fundamental role in the nuclear field for evaluating the neutron embrittlement of the reactor pressure vessel, specifically in the framework of the so-called Enhanced Surveillance Approach, developed at SCK•CEN and aimed at extracting as much information as possible from Charpy impact tests performed with an instrumented striker. Careful analysis of the instrumented force/deflection traces allows defining important parameters which can help investigate material characteristics such as flow properties, microcleavage fracture stress, crack arrest behavior and alternative characteristic (index) temperatures. For this advanced approach to be successfully applied, confidence in the quality of instrumented force values must be high; as a consequence, extensive research has been performed in order to establish an optimal procedure for the verification of instrumented Charpy strikers. Various approaches will be described in this paper and their applicability and effectiveness discussed. A procedure based on the comparison between yield stresses measured from tensile tests and calculated from instrumented Charpy curves has recently been adopted at SCK•CEN as the recommended in-house procedure for verifying instrumented strikers. This method has shown that for all strikers investigated, the so-called "dynamic" calibration (based on the equalization of dial and calculated energies) yields the most accurate results.

KEYWORDS: instrumented Charpy tests, Enhanced Surveillance Approach, dynamic yield stresses, "dynamic" calibration of instrumented strikers

Introduction

The Charpy impact test plays a fundamental role in the nuclear field for assessing the reactor pressure vessel (RPV) lifetime; more specifically, the shift of the impact transition curve indexed at 41 J is used to estimate the degree of embrittlement of the RPV in terms of fracture toughness, using a lower bound curve [1].

At SCK•CEN, the reliability of force measurements obtained from instrumented Charpy tests is of primary importance in view of the so-called Enhanced Surveillance Strategy of nuclear reactor pressure vessel steels [2–5]. This advanced approach can help to overcome several deficiencies of the conventional RPV surveillance and regulatory practice, such as the empirical indexing of fracture toughness to the 41 J Charpy energy level. Indeed, it has been shown that the effects of neutron exposure on fracture toughness could be more reliably assessed by using alternative transition temperatures obtained using the Load Diagram Approach [5].

In the Load Diagram (short for Generalized Load-Temperature Diagram), characteristic force values (yield, maximum, brittle fracture, and crack arrest) are represented and fitted as a function of test temperature. As such, the Load Diagram:

- is directly correlated to the appearance of the fracture surface (SFA);
- represents a straightforward experimental expression of the Davidenkov diagram, linking Ductile-to-Brittle Transition Temperature (DBTT) shifts to irradiation damage mechanisms;
- allows quantifying strain rate effects on the yielding and work hardening capability of the steel.

Moreover, characteristic temperatures obtained from the Load Diagram can more reliably assess the effect of service exposure on DBTT and cleavage fracture toughness than temperatures corresponding to fixed amounts of Charpy absorbed energy (41 J, 68 J) [6].

Manuscript received November 15, 2004; accepted for publication September 25, 2005; published December 2005. Presented at ASTM Symposium on Pendulum Impact Machines: Procedures and Specimens on 8 November 2004 in Washington, DC; T. A. Siewert, M. P. Manahan, C. N. McCowan, and D. Vigliotti, Guest Editors.
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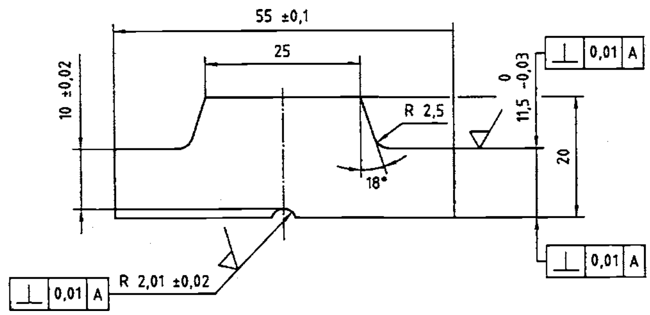

FIG. 1—*Calibration support block suggested by the ISO 14556:2000 standard.*

All this, along with the fact that sometimes large discrepancies are observed between dial energy (KV) and total energy calculated from the instrumented curve (W_t), justifies the emphasis put on the qualification of instrumented force values at SCK•CEN.

Procedures Currently Available for Calibrating an Instrumented Charpy Striker

In an instrumented impact test, the forces applied to the striker are evaluated on the basis of elastic deformations measured by the strain gages glued to the striking edge (tup). To convert strain gage signals into force values, a calibration factor or curve is used; this is normally determined using one of the methods detailed below.

Static Calibration of the Striker Using a Flat Support

Several known force values, normally in steps of 10 % of the total force range of the striker, are applied to the tup under quasi-static conditions. The striker is pressed against a flat support piece, normally similar to an undeformed Charpy specimen (in order to reproduce the nominal contact surface during an actual test). Applied force values versus strain gage voltage readings are taken and eventually fitted in order to derive the calibration factor (or curve).

This calibration, which is performed routinely by most impact machines manufacturers, assumes that the contact between striker and specimen can be approximated by a nonmoving line.

Static Calibration of the Striker Using a "Grooved" Support

The only difference with respect to the previous method is the configuration of the support piece, which has, in the contact area, a shape approximately complementary to the tup profile ("grooved" support, Fig. 1). This support is recommended (but not imposed) by the ISO 14456:2000 standard on Instrumented Impact Testing [7], which therefore assumes that the contact striker/specimen is distributed over the whole curved surface of the tup.

"Dynamic" Force Calibration

The force conversion factor can also be determined, on a test-by-test basis, by imposing equivalence between the dial energy KV (measured independently from the force, using an encoder and/or dial gage, and corrected for friction and windage losses) and the work calculated by integrating the force/displacement test record (W_t). This approach is commonly known (probably using an inappropriate term) as "dynamic" force calibration, in contrast to the previous methods (commonly referred to as "static" calibrations). It may be analytically expressed as follows [8]:

$$C = \frac{Mv_o}{\int_0^{t'} F'(t)dt}\left(1 \pm \sqrt{1 - \frac{KV}{E_p}}\right) \tag{1}$$

where:

C = force calibration factor (in kN/V);
M = mass of the pendulum;
v_o = impact velocity;
$F'(t)$ = uncalibrated force (in V);
E_p = potential energy.

Other calibration procedures have been proposed, such as dynamic verification methods [9,10]. However, these appear sophisticated and require lengthy and costly preparations; their effectiveness and applicability still need to be demonstrated.

What Test Standards Tell Us About Force Calibration

Presently, the only officially issued test standard dealing with Instrumented Impact Tests is ISO 14556:2000 [7]. As far as ASTM is concerned, work is in progress within committee E28.07.08 on a draft standard [11].

However, a rather old ASTM draft standard [12], which never made it to official status due to a sudden drop of interest from the American industry towards precracked Charpy testing, suggested in 1980 an interesting, alternative approach to striker calibration.

ISO 14556:2000 Standard [7]

In the ISO standard, there is no explicit obligation to perform a static calibration; the exact wording is "*Calibration of the recorder and measuring system may, in practice, be performed statically (…)*" (§6.2.2.4); the use of the support block shown in Fig. 1 is suggested, but the use of a flat support piece is not excluded.

Furthermore, the user is encouraged to assess the performance of the instrumentation by comparing KV and W_t (§6.1.2). Should the difference exceed ±5 J, potential issues such as friction, calibration and software need to be addressed.

ASTM Draft Test Standard Method [11]

The reference to the "possibility" of performing a static calibration of the striker is expressed with identical words as in the ISO standard (§5.1.4). As far as the comparison between KV and W_t is concerned, no acceptable range is given but the following is reported: "*It is expected that the total absorbed energy (…) will be in general agreement with the dial and/or optical encoder absorbed energy. Hovever, it must be recognized that the instrumented striker total absorbed energy will not be in exact agreement with the dial energy because the two methods measure different processes and have different calibration requirements*." It's interesting to note that, in previous drafts of this document, an "acceptable" range of ±10 % was suggested as an indication of satisfactory performance of the instrumentation.

ASTM Proposed Method for Precracked Charpy Testing [12]

In this old document, calibration of the load transducer is achieved by impact testing Charpy specimens of a strain-rate insensitive material, which exhibits a maximum force which is independent of the testing speed, and can therefore be easily measured from quasi-static tests performed using a calibrated load cell. Maximum force values from a minimum of three impact tests are expected to correspond to the reference values measured in quasi-static conditions within ±3 %. The suggested material is the "*aluminum alloy 6061-T651 plate*."

An Alternative Approach: Quasi-Static and Dynamic Tests on 6061-T651 Aluminum Alloy

During the 1980s, SCK•CEN had bought a plate of wrought Al alloy 6061-T651 from Effects Technology (Santa Barbara, CA).

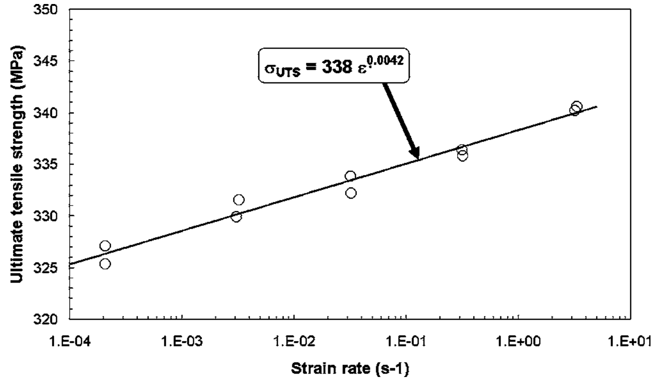

FIG. 2—*Strain-rate sensitivity of the Al 6061-T651 alloy measured from tensile tests.*

In order to verify the effective strain-rate insensitivity of this material[3], tensile tests have been performed at strain rates between 2×10^{-4} s^{-1} and 50 s^{-1} on sub-size cylindrical tensile specimens; tensile tests at high strain rates have been performed according to the prescription of ESIS P7-00 [13]. The results are shown in Fig. 2 in terms of ultimate tensile strength (σ_{UTS}, directly related to the maximum force) as a function of strain rate ($d\varepsilon/dt$); the following strain-rate dependence was obtained:

$$\sigma_{UTS} = 338 \cdot \left(\frac{d\varepsilon}{dt}\right)^{0.0042} \qquad (2)$$

Note that the value of the exponent in Eq 2, which quantifies the strain-rate sensitivity of this alloy, is much lower than the typical values found for conventional steels (0.02 to 0.2) [14].

Based on Eq 2 and Fig. 2, maximum force values obtained from Charpy tests ($F_{m,dyn}$) performed at dynamic velocity (v_{dyn}) must be corrected using the following expression, in order to make them fully comparable to the results of quasi-static tests ($F_{m,st}$ and v_{st}):

$$F_{m,st} = F_{m,dyn} \cdot \left(\frac{v_{st}}{v_{dyn}}\right)^{0.0042} \qquad (3)$$

If we assume v_{st}=0.2 mm/min and v_{dyn}=5.5 m/s, the strain-rate correction from Eq 3 corresponds to about 6 %.

These results from uniaxial tensile tests were confirmed by a series of three-point-bend tests on modified Charpy specimens, conducted at displacement rates in the range 0.0033 to 50 mm/s [15].

Execution of Impact Tests and Comparison with Quasi-Static Test Results

In order to investigate a broader spectrum of maximum force values, as normally experienced in actual instrumented Charpy tests (where measured forces typically range from 0 to 25 kN for conventional low alloy or RPV steels), modified Charpy specimens were tested, with widths (in the notched region) ranging from 7.5 to 15 mm and notch depths from 1 to 3 mm (cross section from 50 to 140 mm^2). The actual test configuration at specimen impact is shown in Fig. 3; using six different specimen types, maximum force values between 3 and 21 kN were obtained.

Instrumented impact tests on modified Charpy specimens have been performed using eight different strikers (three with 2 mm tup radius and five with 8 mm tup radius) belonging to three different pendulums used at SCK•CEN, two of which are in hot cells.

For each striker, an alternative calibration curve was developed by relating dynamic F_m values (in mV, from the strain gage readings) obtained on a specific sample geometry to the corresponding strain rate-corrected reference values (in kN) from quasi-static tests. Such a calibration curve can be directly compared to that obtained from a conventional static calibration. An example is shown in Fig. 4 for one of the 8 mm strikers.

[3]The accompanying certificate issued by Dynatup for this alloy mentions "*a slight strain rate sensitivity for maximum load.*"

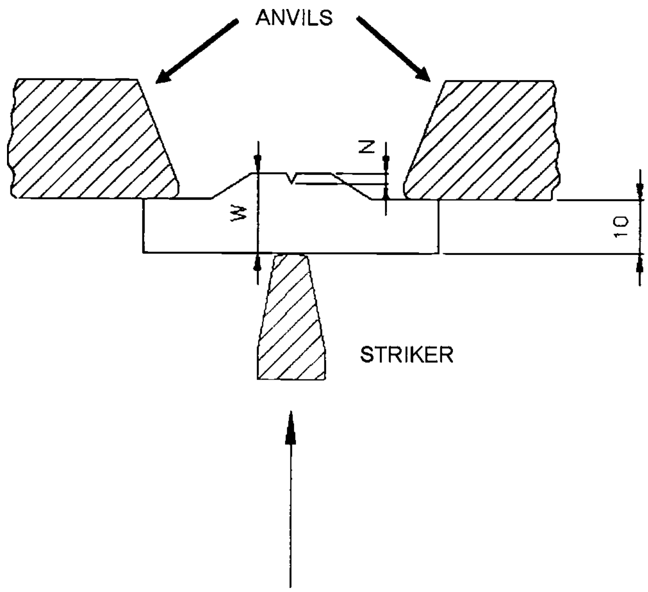

FIG. 3—*Configuration for impact tests on modified Charpy specimens of Al alloy 6061-T651.*

In terms of calibration factor (slope of the calibration curve, in kN/mV) and considering all the investigated strikers, application of this procedure resulted in differences between −8 % and +15 % with respect to the static calibration.

Verification of the Calibration Curves Using the Load Diagram Approach

In order to assess the reliability of the different striker calibration methods (static, dynamic, and Al-based), a procedure based on the Load Diagram has been proposed and validated.

The procedure is based on the direct comparison of yield stresses measured from dynamic uniaxial tensile tests ($\sigma_{y,tens}$), performed at strain rates of the order of 10 s^{-1}, and dynamic equivalent yield stresses calculated from instrumented impact tests ($\sigma_{y,Cv}$). For these latter tests, an equivalent strain rate of 10 s^{-1} is assumed [7] and the following expression [16] is used:

$$\sigma_{y,Cv} = \frac{\beta S F_{gy}}{2C_f(W-a)^2 B} \tag{4}$$

where:

$\beta = 1.866$

S=40 mm is the span

F_{gy} is the force at general yield

C_f is a constraint factor equal to 1.274 for a 2 mm striker and 1.363 for an 8 mm striker;

W, a, B are specimen width, notch depth, and thickness.

The verification is based on the following straightforward principle: the most reliable force calibration should correspond to the best agreement between $\sigma_{y,tens}$ (obtained from a fully independent source) and $\sigma_{y,Cv}$. Furthermore, both dynamic yield stress curves should converge towards the results of quasi-static tensile tests at high temperatures (T$\geq$300°C), where the athermal component becomes prevalent. This approach has been implemented using two well characterized pressure vessel steels, 18MND5 [17] and 22NiMoCr37 [18], and applied to all the instrumented impact strikers currently used at SCK•CEN, both outside and inside the hot cells.

Typical results are shown in Fig. 5 for one of the 2 mm strikers, comparing yield stresses from tensile tests (quasi-static and dynamic) and instrumented Charpy tests (using the static and the dynamic calibration).

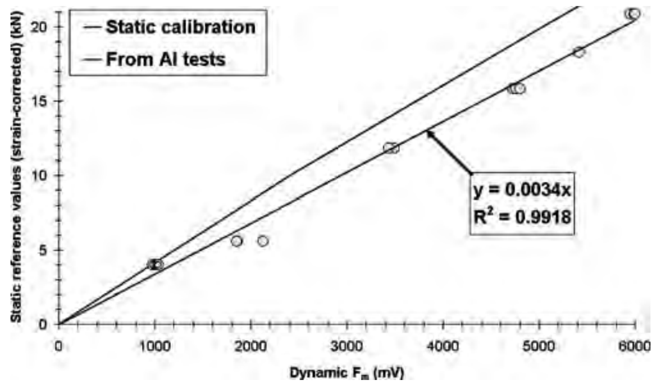

FIG. 4—*Calibration curves obtained for one of the 8 mm strikers. The red line was obtained by applying the static calibration procedure using a flat support, as previously described.*

From our investigations it has emerged that, for all strikers investigated, the "dynamic" calibration (based on the forced equivalence of KV and W_t) provides better accuracy than the static or (for those strikers that were characterized using the Al alloy) the "alternative" Al calibration. Details can be found in Ref [19].

This verification method based on the Load Diagram approach, in which yield stresses from tensile and instrumented Charpy tests are compared, has now been adopted at SCK•CEN for the qualification of instrumented impact strikers, either already in stock and modified (e.g., regaged) or developed in-house. Indeed, research is currently in progress for optimizing the location of strain gages on newly developed tups, using the load diagram method as the quality assurance procedure.

Conclusions

An extensive investigation has been performed in the period 2000 to 2003 at SCK•CEN on the delicate topic of the qualification and verification of force values produced by instrumented Charpy tests.

After reviewing the currently available procedures for the static or "dynamic" calibration of an instrumented striker, a novel approach (although based on a suggestion contained in an old ASTM draft) has been investigated, namely the comparison between maximum forces measured quasi-statically and dynamically on samples of an almost strain-rate insensitive aluminum alloy (6061-T651). This allowed obtaining, for several strikers in use at SCK•CEN, alternative calibration curves relating strain gage response to impact forces.

Finally, a quality assurance procedure for the assessment of the most reliable striker calibration has been developed, based on the comparison of yield stresses measured from quasi-static and dynamic tensile

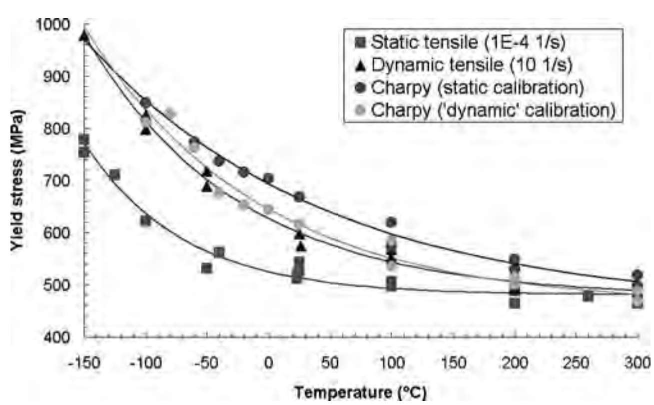

FIG. 5—*Comparison of yield stresses measured from tensile and instrumented Charpy tests for one of the 2 mm strikers investigated; values corresponding to the "dynamic" calibration are in much better agreement with tensile data than those of the static calibration. Tensile and impact tests were performed on the 18MND5 RPV steel.*

tests and evaluated from Charpy forces at general yield (the Load Diagram approach).

Application of this procedure to the instrumented strikers used at SCK•CEN showed that, in all cases, the so-called "dynamic" calibration (based on the equalization of dial and integrated absorbed energies) provides the highest accuracy and reliability; therefore, this methodology will be routinely used in our laboratory when evaluating characteristic forces from instrumented Charpy tests.

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Stock #: STP1476