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Evaluation of Bias for Two Charpy Impact Machines with the Same Instrumented Striker*

ABSTRACT: Two Charpy machines were used to test NIST verification specimens at three energy levels: low energy (~15 J at −40°C), high energy (~100 J at −40°C), and super-high energy (~240 J at room temperature). The study evaluates the differences observed for the bias between two impact machines and the variation in test data for instrumented versus non-instrumented impact tests. The machines used for testing were of very similar design, and all tests were performed with the same instrumented striker (switched between machines). After testing, the raw force/time data were used for the analyses, without correcting instrumented data by matching absorbed energies measured by the machine encoder (KV) and calculated under the force/deflection test record (W_t). The characteristic forces at general yield (F_{gy}) and the maximum forces (F_m) were determined in accordance with ASTM E2298-09 from the instrumented impact record that was used to calculate the total impact energy (W_t). The findings show the following: (1) one machine consistently produced higher absorbed energy values than the other machine; (2) the variation in W_t is significantly lower than the variation in absorbed energy measured in the non-instrumented test (KV) for a given machine and energy level; (3) the relative differences between KV and W_t increased with increasing absorbed energy levels; (4) variations in maximum force are lower than variations in absorbed energy values; (5) instrumented data indicate that the variation in the curves is very small up to maximum force, and that differences in absorbed energy mainly occur during fracture propagation (post-maximum force data); (6) data from these two independent measures of absorbed energy indicate that scatter is due primarily to material variability; and (7) the bias between the two machines is significantly reduced when the same striker is used for testing.

KEYWORDS: absorbed energy, bias, Charpy impact test, instrumented impact tests, instrumented striker, verification specimens

Introduction

The absorbed energy in a Charpy impact test is measured as the loss in energy from a pendulum that impacts and breaks a notched-bar test specimen (Fig. 1). Absorbed energy, typically measured by an optical encoder on the machine for detecting fall and rise angles of the pendulum hammer, is indicated by the symbol KV. Another way to measure the energy absorbed in a Charpy impact test is to instrument the striker with strain gages and measure the force on the striking edge of the pendulum. In an instrumented impact test, the force on the striker is measured as the specimen is impacted and displaced through the anvils of the machine during fracture. The total impact energy, indicated by the symbol W_t, is measured in the instrumented test as the area under the force-displacement curve. Instrumented (W_t) and non-instrumented (KV) measures of absorbed energy can be taken simultaneously on the same machine using the same specimen to provide two independent measures of absorbed energy.

Differences between striker designs, specimen-machine interactions, energy losses due to friction and vibrations, and other factors affect the differences between the two measures of absorbed energy. Much progress has been made on standardization of the Charpy test [1] and critical variables influencing the absorbed energy are now recognized, particularly for non-instrumented impact tests [2,3]. Less work has been done to consider if such variables influence instrumented and non-instrumented tests in the same

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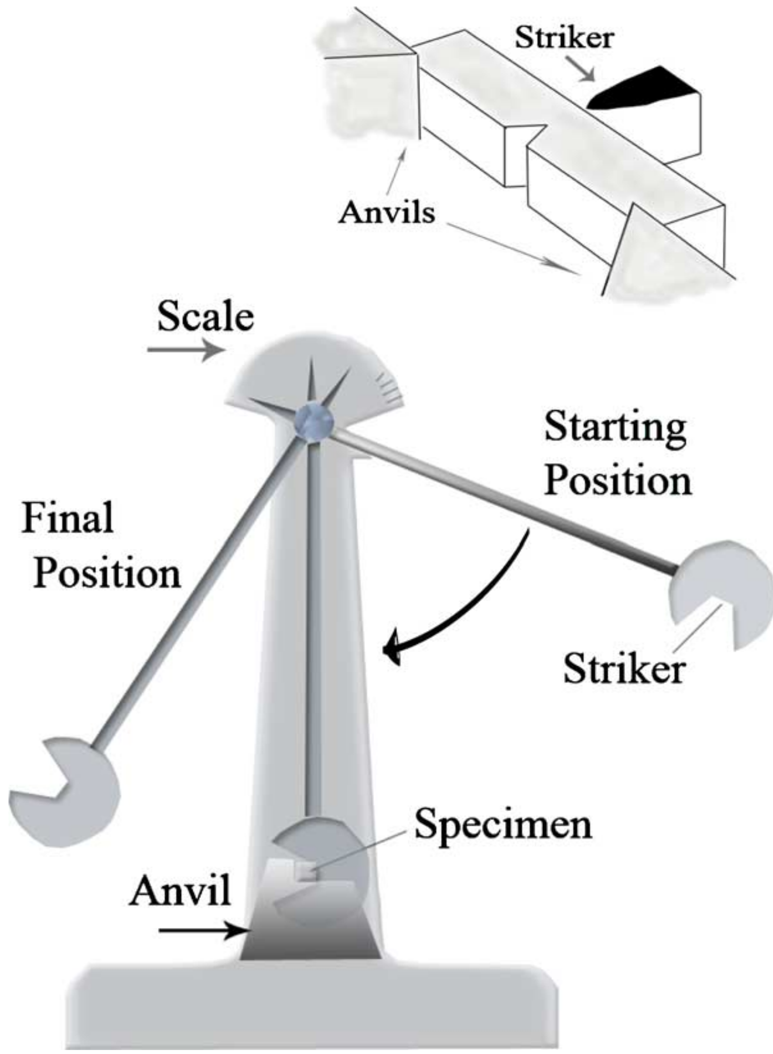


FIG. 1—*In a Charpy V-notch impact test, a pendulum with a striking edge is released from a starting height and impacts a specimen positioned against two anvils. The specimen breaks and the final height of the pendulum is used to determine the energy loss due to the impact.*

manner and magnitude, but recent results indicate similar effects of variables for instrumented and non-instrumented test results [4].

In this paper, we consider differences and similarities between two independent measures of absorbed energy. To limit variables in this comparison, two machines of very similar design (from the same manufacturer) were used for the testing, and the same instrumented striker was used on both machines (switched from one to the other). With these limited variables, any bias between the absorbed energies measured on the two machines will be evaluated. Of particular interest here is whether the biases for instrumented and non-instrumented results are similar or different, and how the differences between these two independent measures of absorbed energy might be used to reduce bias among Charpy impact reference machines (i.e., pendulums maintained by national laboratories that certify Charpy verification specimens, such as NIST in the United States).

Material and Experimental

NIST verification specimens of three energy levels were used in this study: low energy ($\sim$15 J at −40°C), high energy ($\sim$100 J at −40°C), and super-high energy ($\sim$240 J at 20°C). These samples were chosen for their homogeneity, to minimize the contribution of material variability in the study. The materials are AISI/SAE 4340 steel, quenched and tempered, for the low and high energy levels, and T-200 steel (18Ni-0.7Ti maraging steel) for the super-high energy level. Additional information on the materials used

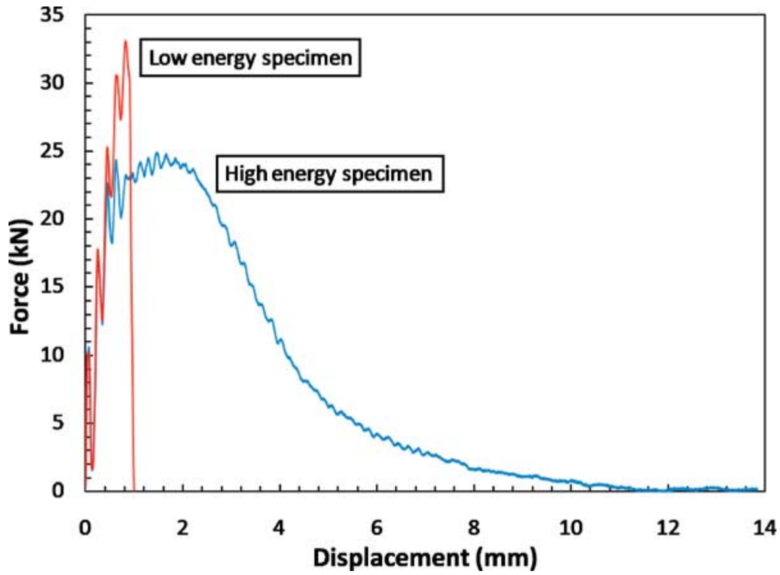


FIG. 2—*Example curves showing characteristic shapes of low energy brittle fracture and high energy fully ductile fracture.*

can be found in Ref 5. Testing was done with an instrumented 8 mm radius striker that conforms to both the ASTM E23 [6] and ISO 148-1 [7] requirements. Tests were conducted in compliance with ASTM E2298-09 [8] for instrumented impact testing.

For each energy level, 25 to 27 instrumented tests were performed on each of the Charpy machines with the same instrumented striker. When testing was completed on one machine, the striker was removed and installed on the other machine. The striker had been calibrated statically as recommended by the current test standards (ISO 14556:2000 [9] and ASTM E2298-09). After testing, the raw force/time data were used for the analyses without correcting force values based on the equivalence between KV and W_t (as allowed by ASTM E2298-09, section 7.2.6).

The two Charpy machines used were reference machines, made by the same manufacturer. The first machine, coded TO2, has a capacity of 358.5 J and an impact velocity of 5.12 m/s. The second machine, coded TO3, has a capacity of 407.7 J and an impact velocity of 5.47 m/s. Because the masses of the hammers are identical for the two machines (27.287 kg), the differences in capacity and impact velocity stem from the higher falling (starting) angle of the TO3 pendulum (134.1° compared to 119.2° for TO2).

The characteristic forces at general yield (F_{gy}) [4] and the maximum forces (F_m) were determined in accordance with ASTM E2298-09 from the instrumented impact record that was used to calculate the total impact energy (W_t). As shown in Fig. 2, the curve shapes differ significantly for low energy (brittle) and high energy (ductile) specimens, and this changes how the yield and maximum forces are determined. For brittle materials, yield force is not well defined, and the maximum force is typically determined as the highest point just prior to fracture (steep force drop). For fully ductile materials, the determination of the general yield force requires operator judgment to estimate the elastic slope, which intersects the fitted curve of the data around the maximum force (see ASTM E2298-09 for further information). The maximum force for fully ductile materials is determined by software as the maximum of the fitting curve following the onset of general yield.

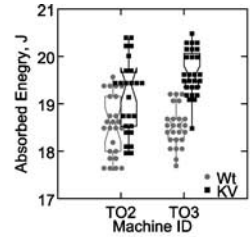
Results

Bias Between Machines

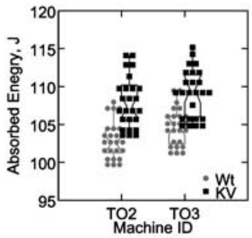
Overall, the differences in the test results between the machines are small, as shown in Fig. 3. The TO3 machine consistently produced slightly higher absorbed energies than the TO2 machine for both W_t and KV. Differences between machines were generally less than 2 % except at the low energy level, where scatter is typically higher.

[4]Note that forces at general yield were not determined for low energy specimens, because in the case of fully brittle behavior the occurrence of general yield is questionable.

Low Energy	W_t, J		KV, J	
	TO2	TO3	TO2	TO3
N of Cases	25	25	25	27
Minimum	17.53	17.69	17.92	18.48
Maximum	19.47	19.24	20.35	20.48
Range	1.94	1.55	2.43	2.00
Mean	18.46	18.52	19.14	19.65
STD abs	0.63	0.41	0.78	0.47
STD rel	3.39 %	2.22 %	4.06 %	2.41 %
Bias rel	0.32 %		2.60 %	



High Energy	W_t, J		KV, J	
	TO2	TO3	TO2	TO3
N of Cases	25	25	25	25
Minimum	99.34	100.94	103.27	104.50
Maximum	107.90	109.50	114.07	115.15
Range	8.56	8.56	10.80	10.65
Mean	102.76	104.69	107.95	109.19
STD abs	2.54	2.41	3.31	3.13
STD rel	2.47 %	2.30 %	3.07 %	2.87 %
Bias rel	1.84 %		1.14 %	



Super-high	W_t, J		KV, J	
	TO2	TO3	TO2	TO3
N of Cases	25	25	25	31
Minimum	211.32	214.63	225.59	226.79
Maximum	228.01	230.65	249.26	257.25
Range	16.69	16.02	23.67	30.46
Mean	220.80	222.89	239.33	239.60
STD abs	3.93	4.30	5.56	6.51
STD rel	1.78 %	1.93	2.32 %	2.72 %
Bias rel	0.94 %		0.11 %	

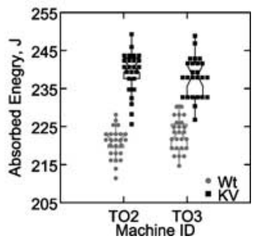


FIG. 3—*Statistics and box plots of the W_t and KV data for the low, high, and super-high energy levels. The relative standard deviation (STD rel) is obtained by normalizing the absolute standard deviation (STD abs) by its mean energy. The relative bias is calculated as the change in the mean energies relative to the TO3 machine, i.e., (TO3–TO2)/TO3. Note that in some cases, the number of W_t values is smaller than the number of KV values due to extra non-instrumented tests being performed or a failure in the instrumented data acquisition.*

Further evaluation of the bias between the TO2 and TO3 machines is made by comparing mean values and standard deviations for each test parameter and energy level in Table 1. In addition, the statistical significance of the differences between mean values is assessed by means of the unpaired *t*-test [10]. The degree of statistical significance depends on the value of the two-tailed probability[5] P using a threshold value of 0.05 (95 % confidence level), as follows:

- $P > 0.05 \rightarrow$ not significant
- $0.01 < P < 0.05 \rightarrow$ significant
- $0.001 < P < 0.01 \rightarrow$ very significant
- $P < 0.001 \rightarrow$ extremely significant.

Before performing the *t*-test, the Grubbs' test (also known as the maximum normed residual test) [11,12], was applied to detect the presence of outliers in the data sets, under the hypothesis that these data can be approximated by a normal distribution. The hypothesis of normality was successfully verified using both the Shapiro–Wilk test [13] and the Anderson–Darling test [14]. Only two outliers were detected, both for the TO3 machine, one among the F_m values of the high energy specimens and one among the W_t values of the super-high energy specimens. After removing the outliers from the data sets, the Grubbs' test was repeated, but no more outliers were detected. The data in Table 1 refer to the various data sets after the application of the Grubbs' test (outliers removed).

Reviewing the data in Table 1, significant differences between the two machines are consistently identified with force data, but not as much with energy data. The ability to better measure differences between the two machines with the force data is due to the lower variation in the force data, resulting in better separation of the data in the analysis. However, it is reasonably clear from the plots in Fig. 3 that the

[5]In statistical hypothesis testing, P is the probability of obtaining a value of the test statistic at least as extreme as the one that was actually observed, given that the null hypothesis (i.e., no difference between the means) is true. Distributions of absorbed energy values and maximum forces are approximately normal.

TABLE 1—*Results of the instrumented Charpy tests performed on the TO2 and TO3 machines and outcome of the t-test. Both the absolute (Abs) and relative (Rel) standard deviations are given.*

Parameter	Energy Level	Test Machine	*N*	Mean Value	Abs Std.	Rel Std. (%)	*P*	Result *t*-test (*Difference Is…*)
F_{gy} (kN)	High	TO2	25	20.61	0.128	0.62	$<$0.0001	Extremely significant
		TO3	25	20.86	0.084	0.40		
	Super-high	TO2	25	20.32	0.190	0.94	$<$0.0001	Extremely significant
		TO3	26	20.63	0.221	1.07		
F_m (kN)	Low	TO2	25	32.62	0.394	1.21	0.0043	Very significant
		TO3	25	32.13	0.713	2.22		
	High	TO2	25	24.28	0.078	0.32	$<$0.0001	Extremely significant
		TO3	24[a]	24.44	0.094	0.39		
	Super-high	TO2	25	25.57	0.072	0.28	$<$0.0001	Extremely significant
		TO3	26	25.71	0.062	0.24		
W_t (J)	Low	TO2	25	18.46	0.626	3.39	0.6926	Not significant
		TO3	25	18.52	0.412	2.22		
	High	TO2	25	102.76	2.539	2.47	0.0084	Very significant
		TO3	25	104.69	2.407	2.30		
	Super-high	TO2	25	220.80	3.928	1.78	0.0777	Not significant
		TO3	25[a]	222.89	4.298	1.93		
KV (J)	Low	TO2	25	19.14	0.777	4.06	0.0058	Very significant
		TO3	27	19.65	0.474	2.41		
	High	TO2	25	107.95	3.314	3.07	0.1778	Not significant
		TO3	25	109.19	3.132	2.89		
	Super-high	TO2	25	239.33	5.560	2.32	0.8686	Not significant
		TO3	26	239.60	6.514	2.72		

[a]One outlier removed.

absorbed energy (W_t and *KV*) results from the TO3 machine are systematically higher than the results for the TO2 machine. This is consistent with the observation that the forces associated with the TO3 machine were significantly higher than for the TO2 machine, and indicates a small consistent bias between the machines. A similar trend for bias is found for the absorbed energies measured with the encoder (*KV*).

Variation in Measurements

As already noted, the variation associated with the force scale is lower than that for the energy scale. This is particularly true for the maximum force values (F_m) for fully ductile materials, which have little dependence on operator input for identification. Variations of less than 0.5 % were found for maximum force values, compared with a range of 1.78 % to 3.07 % for the relative variations of the W_t and *KV* measurements.

Variations in force and energy values tend to have similar magnitudes for both machines at a given energy level, and some trends are apparent. For example, the relative variations for W_t at the high energy level are 2.47 % and 2.30 % for the TO2 and TO3 machines, respectively, and variations in *KV* at the high energy level are 3.07 % and 2.87 % for the TO2 and TO3 machines. In this case, the two machines have similar variations for a given parameter, and the small difference in the variation between machines is similar for both parameters (W_t and *KV*). In other cases, such as the W_t and *KV* variations at the low energy level, variations differ more between machines for a given parameter, and this difference and the magnitude of variation is similar for both parameters (3.39 % and 2.22 % compared with 4.06 % and 2.41 %). These types of correlations might be expected, because these data sets are from the same impact tests, but W_t and *KV* are independently measured in the test and vary independently. The results show that the variation in *KV* is systematically higher than the variation in W_t.

Details of the force-displacement curves for the instrumented impact tests show several characteristic trends that help to explain the variation in absorbed energy, and why it is larger than the variation in maximum force. In Fig. 4, instrumented data for ten high energy specimens (namely, the five lowest *KV* and the five highest *KV* tests) are compared as an example to show that the curves are very similar up to the maximum force. The primary differences in the curves occur after the maximum force at displacements between 2 and 8 mm. In this particular example, the differences between the curves represent a 10.5 %

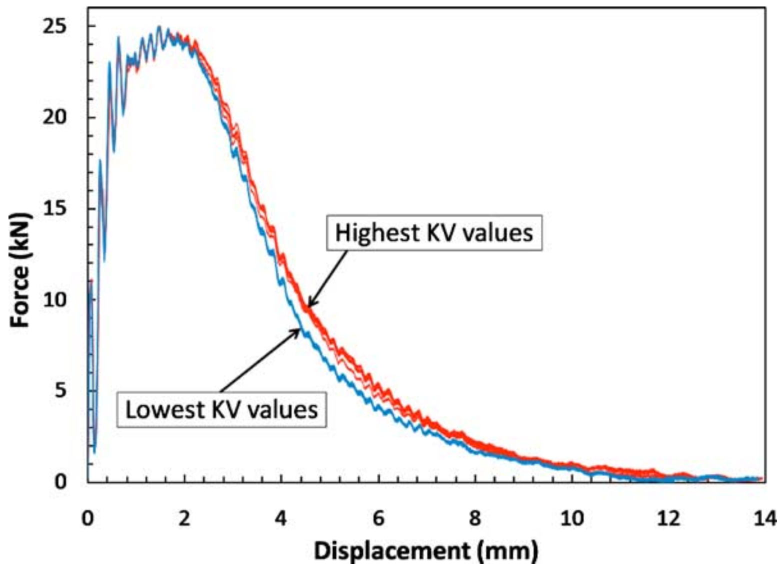


FIG. 4—*Force-displacement curves for the five lowest and the five highest high energy specimens, tested with the TO2 machine.*

difference in energy (area under the curve, W_t) and a difference of only 0.8 % in maximum force (peak of fitted curves near 2 mm displacement, F_m). Comparison between other tests at the high and super-high energy levels all showed similar trends, and trends for data from both machines were similar. Differences between force-displacement curves at displacements past the maximum force differ in details of how and where the curves diverge. The most significant differences occur during fracture propagation (post-F_m), not during fracture initiation (pre-F_m). Indeed, for the ten tests depicted in Fig. 4, mean absorbed energies up to 1.47 mm deflection (which corresponds to the ninth force peak) only differ by 1 % between lowest and highest *KV* values, whereas the difference is 9.7 % for mean absorbed energies from 1.47 mm deflection to the end of the test.

Correlation Between Instrumented and Non-Instrumented Data

The absorbed energies measured with the instrumented and non-instrumented methods are shown in Figs. 5 and 6 for both machines. As shown previously in Fig. 3, the non-instrumented results (*KV*) are consis-

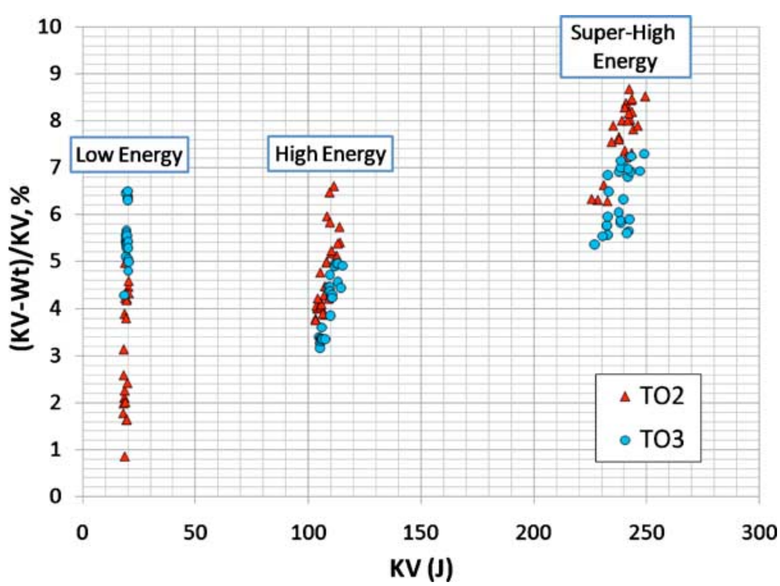


FIG. 5—*Relative differences between KV and W_t for the two impact machines and for the different energy levels.*

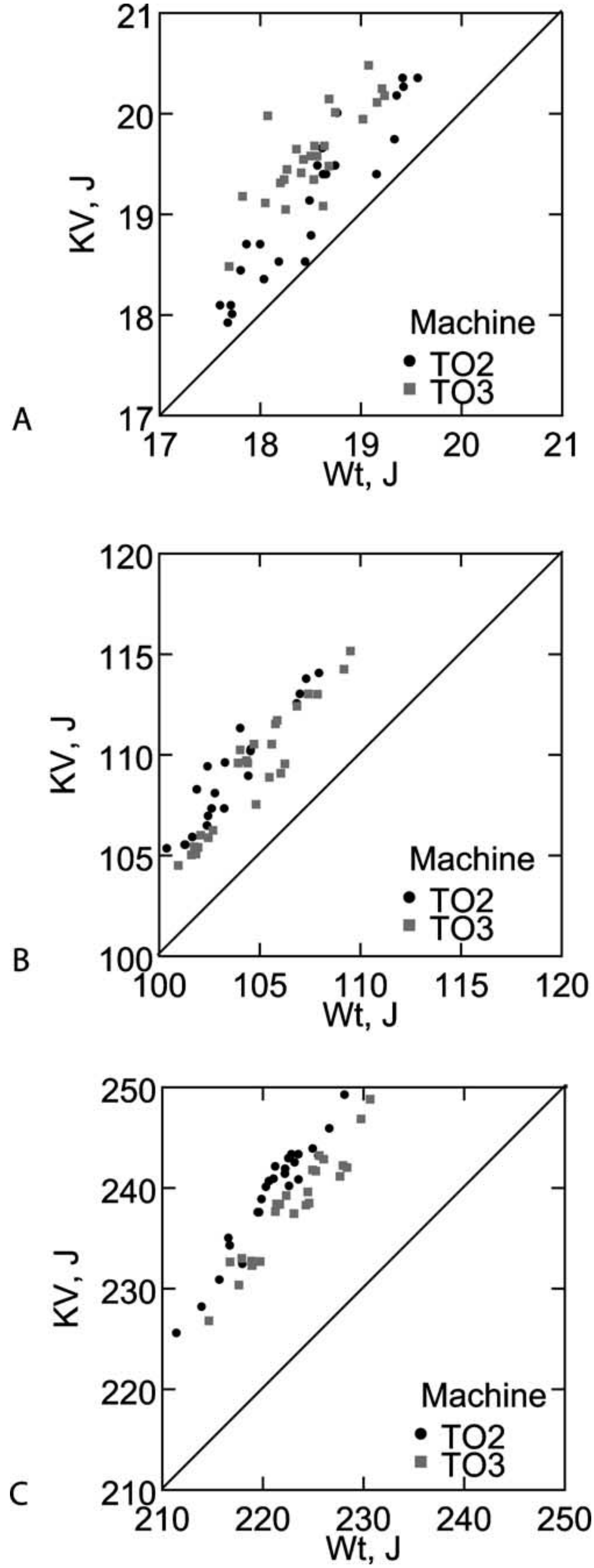


FIG. 6—*Trends for non-instrumented (KV) versus instrumented (W_t) absorbed energy measurements are shown for (a) low, (b) high, and (c) super-high energy levels.*

TABLE 2—*Difference between instrumented (W_t) and non-instrumented (KV) absorbed energy measurements at three energy levels.*

Energy Range	Machine	Difference ($KV-W_t$), J	Percent Change from *KV*, %
Low	TO2	19.41−18.46=0.81	4.17
Low	TO3	19.65−18.52=1.13	5.75
High	TO2	107.95−102.76=5.19	4.81
High	TO3	109.19−104.69=4.50	4.12
Super-high	TO2	239.33−220.80=18.53	7.74
Super-high	TO3	239.60−223.54=15.46	6.54

tently higher than the instrumented results (W_t) on both machines, at all energy levels. This result is not surprising, considering that the instrumented signal is unable to pick up contributions to the absorbed energy due to hammer vibrations, secondary impacts, etc. Figure 5 shows that relative differences in *KV* and W_t are largest at the super-high energy level, and scatter is greatest at the low energy level. For low energies, TO3 tends to provide larger differences than TO2, while the opposite is observed for high and super-high energies. The trend for the relative difference with energy level for the TO2 machine is reasonably linear, compared with the trend for the TO3 machine.

In Table 2, the differences are calculated and normalized with respect to *KV*. The percent differences for the low and high energy levels are between 4 % and 6 %, with an average for the high energy level of 4.5 %. The changes are greater than 6 % at the super-high energy level, with an average of 7.1 %. These results show that the differences due to the measurement approach used on a given machine are at least twice as large as the bias between the machines using a given measurement approach.

In Fig. 6, the detailed trends for the KV-W_t data are shown. For a given machine, the two independent estimates of absorbed energy show an obvious correlation. The *KV* values increase slightly more rapidly than the W_t values, as confirmed by the slope of the linear regressions between *KV* and W_t, which ranges from 1.01 to 1.37. This likely reflects characteristics associated with the particular striker that was evaluated here. The trends also provide convincing evidence that much of the scatter in the energy values is due to variability in the material and not in the test machine. This is evident from the fact that differences between the two measures of absorbed energy used are small (narrow scatter bands) compared with the range in energy measured for the individual energy levels. Both machines show similar trends at all three energy levels.

Influence of Striker Design on the Bias Between Machines

The influence of the striker was noted when comparing super-high energy level data from the TO2 machine equipped with an instrumented striker to data from the same machine equipped with a non-instrumented striker. This comparison was possible in this case, because data was available from a previous test campaign when the same specimens were tested using a non-instrumented striker. The comparison between *KV* values for this data is given in Table 3. The finding here shows a larger difference in mean energy due to changing the striker on a given machine than was found between different machines with the same striker.

Table 4 shows that the difference between mean *KV* values between TO2 and TO3 changes from 6.98 J when the machines have different strikers (TO2 non-instrumented, TO3 instrumented) to 0.27 J when the same (instrumented) striker is used on both pendulums. So, the inter-machine bias is greatly reduced when both machines are equipped with the same striker (or two strikers of very similar design).

The findings of Tables 3 and 4 are likely due to minor changes in stiffness in the striker due to modifications needed to mount the strain gages.

TABLE 3—*KV results from super-high energy specimens on the TO2 machine using two different strikers.*

Striker	*N*	Average (J)	Difference (J)
Non-instrumented	25	246.58	7.25
Instrumented	25	239.33	

TABLE 4—*KV results from super-high energy specimens on the TO2 and TO3 machines using two different strikers and the same strikers.*

Machine	Striker	N	Average (J)	Difference (J)
TO2	Non-instrumented	25	246.58	
				6.98
TO3	Instrumented	26	239.60	
				0.27
TO2	Instrumented	25	239.33	

Discussion

We tested Charpy impact specimens at three energy levels with two impact machines of almost identical design. The same instrumented striker was used on both machines to remove striker design as a variable. For each test, the absorbed energy was measured using two independent approaches: (1) Potential energy loss of the pendulum (KV) and (2) total work spent as calculated from the measured time-force record (W_t).

A small bias in the energy measurements between the machines was identified with both instrumented and non-instrumented test results (W_t and KV). In some cases, the perceived bias was not statistically significant, but consistent differences between the machines show the differences to be characteristic of the machines. The TO3 machine had higher W_t and KV values than the TO2 machine at every energy level. Estimates of the bias between the machines obtained with either technique were always less than 3 % and often less than 1 %. This is good with respect to the verification requirements of ASTM E23, which allow a maximum of 10 % bias between impact machines within its test program.

Generally, differences between the machines were more significant for instrumented forces than for absorbed energies. In the case of fully ductile tests (high and super-high energy specimens), the TO3 machine delivers significantly higher forces, whereas the opposite is observed for more brittle tests (low energy specimens). These findings are consistent with the fact that the only structural difference between the two test machines is the impact speed, which is higher for TO3. A higher loading rate is expected to promote early fracture for brittle materials and higher crack resistance for ductile materials. Indeed, crack initiation is assumed to occur in Charpy specimens approximately midway between F_{gy} and F_m [15,16], except in the case of fully brittle failure (where it coincides with maximum force).

The variation in the maximum force measured on a given machine was smaller than the variation measured for absorbed energy. This lower variation in force, and in the force-displacement records leading up to the maximum force, clearly contributes to a lower variation in W_t (compared with KV). Detailed evaluation of force-displacement curves indicates that the variation in W_t is mostly due to events that occur after the maximum force is reached, during fracture propagation, and while the specimen is interacting with the anvils and striker. So, for the 4340 steels tested, the results show that initiation of the crack at the notch is not a major contributor to the scatter in the test.

Differences in the absorbed energy measured with instrumented versus non-instrumented techniques (on the same machine) are to be expected [17]. Small differences ($\leq$5 %) are related to how the absorbed energy is measured for the two techniques. For example, secondary strikes of specimens against the striker absorb measurable energy from the swinging pendulum, but do not show up on the force-displacement curve of the instrumented test, because they occur after the sample is ejected from the anvils. Along these same lines, energy losses due to vibration of the pendulum during impact result in similar differences. For these reasons, a good striker design and calibration should not be expected to match the absorbed energy scale of the machine exactly. Considering these and other differences, it is argued that the instrumented value (W_t) should be lower than the non-instrumented value (KV). Data here show that W_t was consistently lower than KV, and the underestimation is in the range of 4 % to 8 % of the average KV value, as shown in Table 2. The mean relative difference is 5.4 % for TO2 and 5.5 % for TO3, which suggests that the trend depends primarily on the instrumented striker design. The larger difference in W_t and KV at the super-high energy levels suggests room for improvement in the striker design. However, why the trends in these differences are not more similar for the two machines using the same striker is not apparent.

Large differences ($>$5 %) between instrumented and non-instrumented results are typically attributed to poor design or inadequate static calibration of the instrumented striker. In both cases, there has been a tendency to "adjust" the instrumented data (W_t) using the non-instrumented data (KV) by imposing $W_t = KV$ [18]. Clearly, this approach has some practical merit, but it only eliminates the bias between the W_t

and *KV* results for a particular machine. Of more interest is the use of well designed instrumented strikers that are traceable to primary force and displacement standards (length or time) to reduce the bias between machines in general [19]. From this viewpoint, the calibration potential of the instrumented method may help reduce bias between Charpy impact machines.

Reviewing the results for high and super-high energy levels presented here, a dynamic calibration might be envisioned for instrumented testing that uses a reference curve to normalize the first portion of the force-displacement curve for the machine being calibrated (up to the maximum force). This calibration might offer an approach where the traceability of the result is clear and well documented, and could provide a rational basis for defining bias between impact machines with reference to a common international scale for absorbed energy based on force and time. Much practical work will be needed to further this goal, and it is likely that the approach can only be useful on reference machines that use strikers of very similar design and performance (by agreement and standardization).

Conclusions

The main conclusions for the two machines and the instrumented striker investigated here can be summarized as follows.

- One machine produced consistently higher absorbed energy values than the other.
- Relative variations in maximum force are lower than variations in absorbed energy (W_t and KV).
- The variation in W_t is systematically and significantly lower than the variation in KV. Data scatter appears to primarily stem from material variability.
- The differences between KV and W_t tend to increase with increasing absorbed energy levels.
- Instrumented data show that variations in the curves are quite small up to maximum force, and differences in absorbed energy (W_t) are primarily occurring during fracture propagation (post-maximum force data).
- Differences in results for instrumented versus non-instrumented strikers on the same machine are as expected and indicate a reasonably good striker design and static calibration.
- Machine bias is significantly reduced when the same striker is used for testing.
- Further study is warranted to determine if the use of F_m or W_t can serve as the basis for a calibration method to reduce bias among Charpy impact reference machines.

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