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The Influence of Instrumented Striker Configuration on the Results of Dynamic Toughness Testing

Work performed during a 3-month secondment at NIST, Boulder CO (USA), June-August 2008

Enrico Lucon

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SCK•CEN
Boeretang 200
BE-2400 Mol
Belgium

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SCK•CEN
Boeretang 200
BE-2400 Mol
Belgium

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Studiecentrum voor Kernenergie
Centre d'étude de l'énergie Nucléaire
Boeretang 200
BE-2400 Mol
Belgium

Phone +32 14 33 21 11
Fax +32 14 31 50 21

http://www.sckcen.be

Contact:
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Preface

This work was performed during my secondment at NIST (National Institute of Standards and Technology) in Boulder, Colorado (USA), between June and August 2008.

The contents of this report have been submitted to Journal of Testing and Evaluation for publication on 21 August 2008.

Abstract

Several studies are available on the influence of the edge radius of instrumented strikers (ASTM – 8 mm or ISO – 2 mm) on the results of both non-instrumented and instrumented Charpy tests. This paper investigates the effect of using either a 2 mm or a 8 mm striker when performing dynamic toughness tests at impact loading rates on precracked Charpy specimens. Existing data from tests run in the ductile-to-brittle region (dynamic Master Curve reference temperature) and in the upper shelf regime (ductile initiation fracture toughness and crack resistance curves) have been analyzed. The results show that 2 mm strikers tend to yield lower cleavage fracture toughness in the transition region (although the effect cannot be considered statistically significant), whereas the influence of striker configuration is negligible in the upper shelf regime when data are generated using the low-blow multiple-specimen technique.

Keywords

Instrumented Charpy tests, striking edge radius, dynamic toughness tests, precracked Charpy specimens, dynamic Master Curve, low-blow technique.

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1 Introduction

Impact testing has a history extending back to the 1850's [1], when engineers realized that loading rate can significantly affect material properties. For structural steels, the main result of increasing loading rate is to raise the yield and tensile strength, which in turn causes a decrease in cleavage fracture toughness, an increase in ductile fracture toughness and a shift in the ductile-to-brittle transition temperature. Loading rate must be therefore be considered when designing structures subject to dynamic loading (e.g. earthquakes), ships and road vehicles in collision, aircraft landing gear and, at the highest rates, for projectile or armor ballistics and explosive shock.

The simplest mechanical test that can be conducted to characterize the fracture resistance of metallic materials at dynamic loading rates is the Charpy impact test, which has recently celebrated its first centennial [2,3]. As such, this test cannot provide quantitative information on the fracture toughness properties, since the specimen has a mechanical notch and not a real crack-like defect.

However, measurements of dynamic fracture toughness at impact loading rates can be performed using a Charpy pendulum machine provided that:

- a fatigue precrack is introduced in the sample before it's impact tested, and
- the pendulum striker is adequately instrumented with strain gages, thus allowing the force/time history of the test to be recorded and analyzed.

Loading rates in the order of 10^4-10^5 MPa√m/s can be achieved for impact velocities in the range 1-1.5 m/s.

There is extensive literature concerning dynamic toughness tests on precracked Charpy (PCC) specimens, which have been documented since the mid 70's [4-7]. In spite of these tests being performed even nowadays in many laboratories worldwide, at the time of writing an official test standard is still lacking. Standardization activities are however currently in progress within both ASTM subcommittee E08.07 [8] and ISO technical committee TC164/SC4F [9]. It is therefore expected that dynamic toughness tests on PCC specimens will be officially standardized in ASTM and ISO within a few years.

The configuration of the pendulum strikers used to perform Charpy tests is not unique, but depends on the test standard followed (Figure 1). Specifically, ASTM E 23 prescribes an 8 mm radius for the leading edge, which produces two relatively sharp corners where the nose radius meets the sides of the striker; ISO 148 (conventional Charpy tests) and 14566 (instrumented Charpy tests) provide for a thinner design with a striking edge of 2 mm radius.

The influence of the striking edge radius (2 mm vs. 8 mm) on "conventional" Charpy parameters, such as absorbed energy, lateral expansion and shear fracture appearance has been extensively studied [10-19]. Less information is available on the effect of striker configuration on instrumented Charpy results, such as forces, displacement or energies [12,16,18,20]. Recently, this author has performed an extensive study on Charpy instrumented data which is currently in publication [21].

As a natural follow-up of [21], this paper investigates the influence of the instrumented striker configuration on the results of dynamic toughness tests, using existing test data generated from PCC specimens tested in the ductile-to-brittle transition region and in the upper shelf regime.

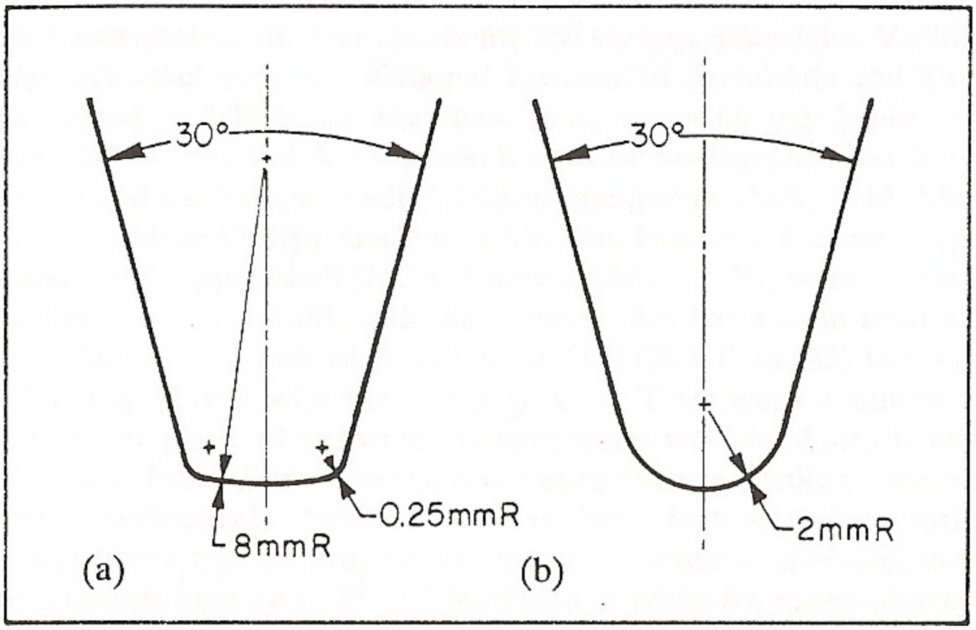

Figure 1 - Schematic drawing of the (a) ASTM (8 mm radius) and (b) ISO (2 mm radius) striker.

2 Tests in the ductile-to-brittle transition region: IAEA CRP8 round robin exercise

2.1 Background

In 2004, the International Atomic Energy Agency (IAEA) launched its Coordinated Research Project n°8 (CRP8) under the title "Master Curve Approach to Monitor Fracture Toughness of RPV Steels: Effects of Bias, Constraint, and Geometry" [22].

The project was subdivided into three Topic Areas, one of which dealt with the effects of loading rate on the Master Curve analysis of fracture toughness data in the ductile-to-brittle transition region [23].

One of the main activities within this Topic Area was the organization of a round robin exercise on fracture toughness testing of precracked Charpy specimens at impact loading rates in the ductile-to-brittle transition region [24].

2.2 Experimental and results

Each of the 10 round robin participants (laboratories from the US, Europe, Japan and Korea) tested 10 PCC specimens using an instrumented pendulum at a velocity of 1.2 m/s. Tests were run between -30°C and 10°C on a typical reactor pressure vessel steel of A533B cl.1 type, denominated JRQ [25]. Its chemical composition and its room temperature tensile properties are given in Table 1 and Table 2 respectively.

Table 1 – Chemical composition of the JRQ steel (weight %).

C	Si	Mn	P	S	Mo	Ni	Cr	Cu
0.07	0.21	1.34	0.02	0.002	0.49	0.70	0.11	0.15

Table 2 – Room temperature tensile properties of the JRQ steel.

Yield strength (MPa)	Tensile strength (MPa)	Elongation (%)	Reduction of area (%)
477	630	26	76

Test results, in term of stress intensity factor K_{Jc} calculated from the J-integral value at cleavage J_c, were analyzed in accordance with the ASTM E 1921-05 test standard, in order to derive the dynamic Master Curve reference temperature $T_{0,d}$. This temperature corresponds to a median dynamic fracture toughness of 100 MPa√m for a specimen having thickness 1 in. = 25.4 mm [26].

Of the 10 round robin participants, 7 used a 2 mm striker (conforming to the ISO design) and the remaining 3 used an 8 mm striker (conforming to the ASTM design).

Table 3 and Figure 2 present the values of dynamic reference temperature reported by the participants as a function of the radius of the striking edge.

Table 3 – Results of the IAEA CRP8 round robin exercise.

Lab	Striking edge radius (mm)	$T_{0,d}$ (°C)
1	2	-1.6
2	2	1.6
3	8	-9.9
4	2	10.0
5	2	2.1
6	2	4.6
7	8	-1.1
8	2	-2.5
9	8	-3.8
10	2	-2.6

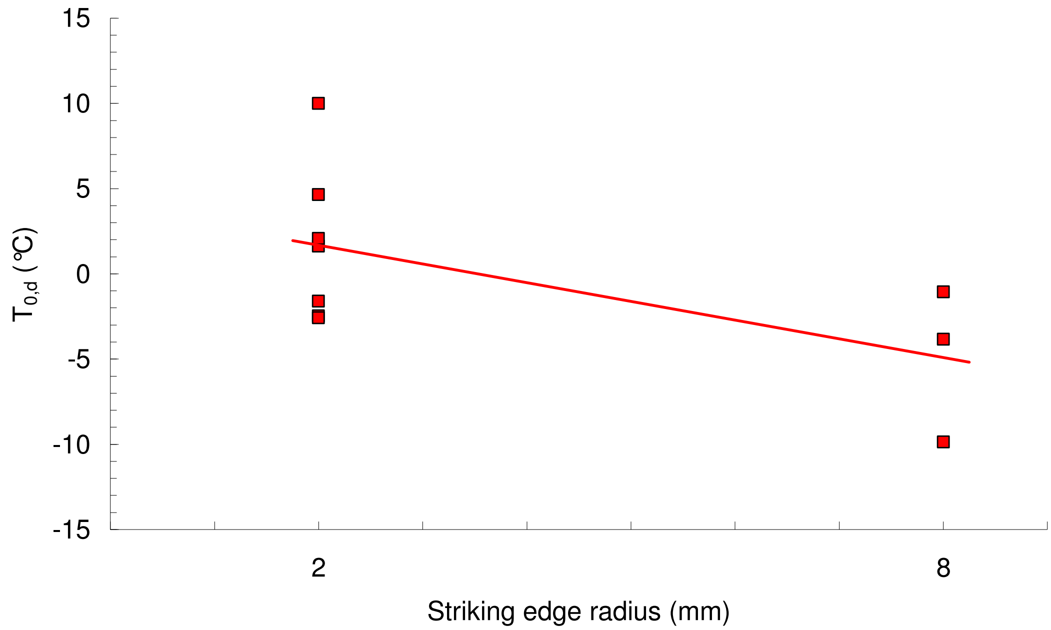

Figure 2 - Dynamic Master Curve reference temperatures measured in the IAEA CRP8 round robin as a function of striking edge radius. The solid line connects average values.

2.3 Discussion

Figure 2 shows that $T_{0,d}$ clearly decreases with increasing striking edge radius. However, the relevance of the observed trend could be questionable due to the limited number of available data.

Therefore we have used the unpaired two sample Student *t*-test [27] in order to assess the real statistical significance of the observed difference between the mean values of $T_{0,d}$ (1.7°C for 2 mm strikers and -4.9°C for 8 mm strikers). This method tests the null hypothesis that the population means related to two independent, random samples from an approximately normal distribution are equal, and can be used if no significant difference is expected between the variances of the two samples.

According to the *t*-test and assuming a confidence level of 95%, the degree of statistical significance of the difference between mean values depends on the value of the two-tailed probability[1] P using a threshold value 0.05 and the following convention:

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

The detailed results of the *t*-test are summarized in Table 4, where DM = difference between the means (2 mm – 8 mm); df = degrees of freedom; SED = standard error of difference.

[1] 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.

Table 4 – Results of the *t*-test applied to the IAEA CRP8 round robin results ($T_{0,d}$).

DM (°C)	95% conf.int. of DM (°C)	t	df	SED (°C)	P	Interpretation
6.59	-0.64 to 13.82	2.1022	8	3.315	0.0687	NOT SIGNIFICANT

According to the *t*-test, the difference observed between the results obtained using the two different strikers is statistically not significant, although the calculated probability (P = 0.0687) is quite close to the threshold of significance (0.05).

The CRP8 round robin results can be further analyzed by considering the individual values of K_{Jc} reported by the participants. Since each participant tested the same number of specimens at the same temperatures following the same strict guidelines, it's appropriate to compare the mean values of K_{Jc} for labs using 2 mm and 8 mm strikers and to assess the statistical significance of the difference using the *t*-test as described above. The results are given in Table 5 below.

Table 5 – Results of the *t*-test applied to the IAEA CRP8 round robin results (K_{Jc}).

Mean 2 mm (MPa√m)	Mean 8 mm (MPa√m)	DM (°C)	95% conf.int. of DM (°C)	t	df	SED (°C)	P	Interpretation
106.5	118.7	-12.2	-27.2 to 2.9	1.6070	96	7.577	0.1113	NOT SIGNIFICANT

The trend is confirmed (8 mm strikers tend to provide higher toughness data, and therefore lower reference temperatures), but once again statistics do not confirm the significance of the striker configuration influence.

A final assessment was made by considering the two large data sets corresponding to all the K_{Jc} results supplied by labs that used 2 mm strikers (68 data points) or 8 mm strikers (30 data points) and analyzing them according to the Master Curve approach (ASTM E 1921-08). The results obtained are shown in Table 6, where: N = number of tests performed; r = number of valid data; $\sigma_{T0,d}$ = standard deviation of the calculated reference temperature.

Table 6 – Results from the Master Curve analyses of all the 2 mm and 8 mm results.

Striking edge radius	N	r	$T_{0,d}$ (°C)	$\sigma_{T0,d}$ (°C)
2 mm	68	62	1.1	4.61
8 mm	30	25	-5.0	5.38

The difference between calculated reference temperatures (6.1°C) is close to the difference between mean values in Table 4, and ±1σ error bands overlap.

This analysis substantially confirms the results of the *t*-test in Tables 4 and 5: a tendency for 2 mm strikers to provide lower toughness is visible, but the influence of striker configuration cannot be statistically confirmed based on the available data.

3 Tests in the upper shelf regime: collaboration between SCK•CEN and IWM

In the mid-80's, SCK•CEN and the Fraunhofer Institut in Freiburg (IWM, Germany) established a collaborative project in which precracked Charpy specimens were tested at impact loading rates in the upper shelf regime [28]. The material tested was a French reactor pressure vessel steel with designation 18MND5 (AFNOR code); chemical composition and room temperature tensile properties are provided in Table 7 and Table 8.

Table 7 – Chemical composition of the 18MND5 steel (weight %).

C	Si	Mn	P	S	Mo	Ni	Cr	Cu
0.175	0.245	1.55	0.008	0.002	0.495	0.64	0.18	0.13

Table 8 – Room temperature tensile properties of the 18MND5 steel.

Yield strength (MPa)	Tensile strength (MPa)	Elongation (%)	Reduction of area (%)
506	659	21.5	73.3

Charpy specimens were extracted from a plate with 118 mm thickness, fatigue precracked to a nominal crack aspect ratio a/W = 0.5 and tested at room temperature using the multiple-specimen "low-blow" technique. The principle of this method consists in limiting the available impact energy for each test, such that it is sufficient to produce a certain stable crack extension, but not enough to fully break the specimen. By selecting different energy levels in a series of tests on nominally identical specimens, a series of different crack extensions Δa_i are produced. From the corresponding dynamic J-integral values calculated from the instrumented force/displacement traces, J_d-Δa curves (*dynamic R-curves*) are constructed and initiation values of dynamic fracture toughness (J_{Qd}) are determined in accordance with ASTM E1820-08.

Two series of PCC specimens of 18MND5 steel were tested, one at SCK•CEN using a 2 mm striker and one at IWM using an 8 mm striker. The results are presented in Table 9, where Δa_Q is the crack extension corresponding to initiation and TM is the tearing modulus (slope of the regression curve at Δa_Q, J_{Qd}).

Table 9 – Results of the upper shelf dynamic toughness tests on 18MND5.

Striking edge radius (mm)	Δa_Q (mm)	J_{Qd} (kJ/m²)	TM (MPa)
2	0.55	654.2	809.2
8	0.55	658.5	764.4

3.1 Discussion

The results obtained from the two striker configurations are practically identical, both in terms of critical toughness and crack resistance curves. The tearing resistance is slightly higher for the ISO striker, but the difference is marginal (6%).

The consistency of the data measured at SCK•CEN at IWM is confirmed by Figure 3, where experimental data and R-curves for the two striker configurations are compared.

This result should not be considered surprising, since it has been shown [17,19,20] that differences in absorbed energies for highly ductile Charpy specimens tested with ASTM and ISO strikers mainly arise from the interactions between the strongly deformed sample and the sharp corners of the 8 mm striker (Figure 1). Another important factor is the increased friction between anvil and specimen when the latter is ejected at the end of the test.

In low blow testing, the samples are only partially deformed and none is bent or wrapped around the striking edge enough to interact with the corners of the ASTM striker. Moreover, the samples are not pushed through the anvils but remain on the supports. Hence, no significant difference should be expected between 2 mm and 8 mm strikers.

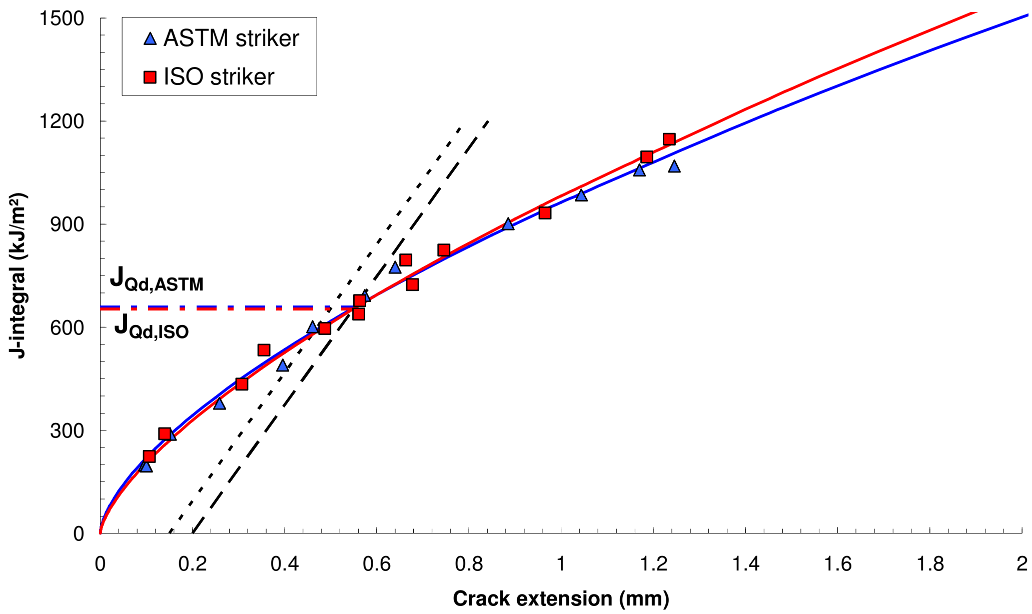

Figure 3 – Results obtained from the dynamic upper shelf tests on 18MND5 using different striker configurations (ASTM and ISO).

4 Conclusions

Our investigation shows that the instrumented striker configuration (ASTM or ISO) does not have a significant influence on the results of dynamic toughness tests performed at impact loading rates on precracked Charpy specimens.

For the ductile-to-brittle transition regime, the results of a recent IAEA CRP8 round robin show that 8 mm strikers tend to provide lower cleavage toughness and therefore higher values of the dynamic Master Curve reference temperature $T_{0,d}$. This could be attributed to the thinner and therefore more "penetrating" design of the 2 mm striker, which might increase stress concentration at the crack tip and therefore promote earlier specimen failure under brittle conditions. However, based on a simple statistical analysis of the available information, the influence of the striker configuration is not statistically significant at the 95% confidence level.

It would be desirable to conduct a more systematic study of striker influence on dynamic Master Curve results, with a more balanced number of tests for each striker configuration.
In the upper shelf regime, tests performed twenty years ago by SCK•CEN and IWM Freiburg using the multiple-specimen low-blow technique show that the striking edge radius has no effect on either initiation toughness or resistance curve. This can be easily understood on account of the

limited plastic deformation of the specimens tested with the low-blow technique, which does not allow interactions between the samples and the 8 mm striker corners or significant friction between the samples and the anvils.

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