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On the Effectiveness of the Dynamic Force Adjustment for Reducing the Scatter of Instrumented Charpy Results

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

Enrico Lucon

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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 were submitted to Journal of ASTM International for publication on 28 August 2008.

Abstract

One of the key factors for obtaining reliable instrumented Charpy results is the calibration of the instrumented striker. An interesting alternative to the conventional static calibration recommended by the standards is the Dynamic Force Adjustment (DFA), in which forces and displacements are iteratively adjusted until equality is achieved between absorbed energies calculated under the test record (W_t) and measured by the machine encoder (KV). In this study, this procedure has been applied to the instrumented data obtained by 10 international laboratories using notched and precracked Charpy specimens, in the framework of a Coordinated Research Project (CRP8) of IAEA. DFA is extremely effective in reducing the between-laboratory scatter for both general yield and maximum forces. The effect is less significant for dynamic reference temperatures measured from precracked Charpy specimens using the Master Curve procedure, but a moderate reduction of the standard deviation is anyway observed. It is shown that striker calibration is a prominent contribution to the interlaboratory variability of instrumented impact forces, particularly in the case of maximum forces.

Keywords

Instrumented Charpy tests, striker calibration, dynamic force adjustment, IAEA CRP8, between-laboratory scatter, dynamic Master Curve.

Table of Contents

1 Introduction

Charpy impact testing of metallic materials has a long history, dating back to the years bridging the 19^{th} and 20^{th} centuries, with the early pioneer works of S. B. Russell [1] and G. Charpy [2]. Instrumented Charpy testing, where the pendulum striker is equipped with strain gages to record the force applied to the specimen during the impact event, is more recent, although the earliest works were published in the 1920's [3].

In the nuclear field, impact testing still plays a fundamental role in the assessment of the reactor pressure vessel (RPV) lifetime. Current regulations [4,5] require to obtain full Charpy transition curves both on the unirradiated and irradiated vessel materials, in order to measure their radiation embrittlement based on the increase of a ductile-to-brittle transition temperature corresponding to a predetermined absorbed energy level (T_{41J}). In the unirradiated condition, the fracture toughness of the vessel materials is assessed by means of a lower bound curve, whose position on the temperature axis is based on a combination of drop-weight and Charpy impact results [4]. After irradiation, the fracture toughness curve is shifted to higher temperatures by an amount that is assumed equal to the above mentioned increase of T_{41J}.

The use of an instrumented striker gives added value to the Charpy tests prescribed by the legislation. Alternative transition temperatures can be defined by constructing the so-called *Load Diagram* (short for *Generalized Load-Temperature Diagram*) [6], in which characteristic force values from the instrumented Charpy traces are plotted and fitted as a function of test temperature. This advanced approach [7-11] allows overcoming 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.

One of the key factors for deriving meaningful and useful data from instrumented Charpy tests is to make sure that the instrumented striker of the impact machine is accurately calibrated, so that the signal of the strain-gages can be reliably converted into force applied to the test specimen.

The conventional approach to calibrating an instrumented impact striker consists in applying several known force values (traceable to a calibrated load cell) and recording the corresponding strain-gage output. Force and strain-gage voltage readings are then fitted by an appropriate regression function to obtain a calibration factor (in the case of a linear fit) or a calibration curve (in the case of other fitting equations). This procedure is commonly known as "static calibration".

Static calibration can be performed with the striker built in the hammer assembly (as recommended by the ISO 14556:2000 standard), but in most cases strikers are removed from the pendulum and installed on a universal testing machine using suitable fixtures. During calibration, force is applied to the striker against a flat surface, typically in the form of an undeformed Charpy specimen, or using a special support test block which features a groove which complements the shape of the striker nose (Figure 1). Alternative calibration approaches [12-14], aimed at more closely simulating the dynamic conditions experienced by the striker during an actual impact test, have been proposed but have not yet generated sufficient consensus.

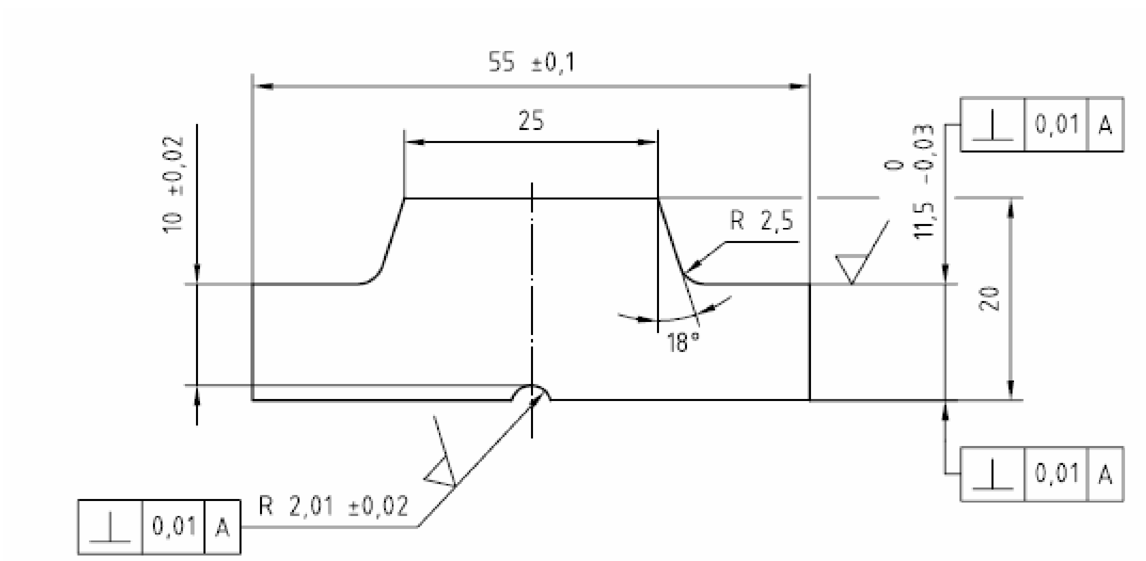

Figure 1 – Support block for the static calibration of instrumented strikers recommended by ISO 14556:2000.

An analytical option for deriving a force calibration factor on a test-by-test basis is the "Dynamic Force Adjustment" (DFA) [15], which is based on postulating the equivalence between:

- KV (the absorbed energy measured by an encoder or a dial gauge indicator, independently from the force), and
- W_t (the work spent for fracturing the specimen, calculated by integrating the instrumented force/displacement curve).

Actually, there would be sound theoretical reasons why the two measurement of absorbed energy should not be considered equal, since KV includes contributions that are unrelated to the fracture event, such as vibrational losses, losses due to secondary collisions, brinelling etc [16,17]. However, these are generally second-order contributions, and the assumption of equivalence between KV and W_t can be considered acceptable for practical purposes. This allows calculating a force conversion (calibration) factor C, in kN/V, using the following expression [18]:

$$C = \frac{Mv_o}{W_t}\left(1 \pm \sqrt{1 - \frac{KV}{W_o}}\right) \tag{1}$$

where M is the pendulum mass (kg), v_o is the impact velocity (m/s) and W_o is the potential energy (J). KV and W_t are also expressed in J.

What happens in practice is generally a two-step process, namely:

(a) instrumented forces are obtained from strain-gage voltage readings using a "conventional" static calibration factor (or curve);

(b) forces and displacements are adjusted through an iterative process (which can be easily implemented, for ex. by using the Solver tool of EXCEL97) until KV = W_t. Ideally, if the static calibration was correctly performed, this adjustment should not exceed 10%.

The currently proposed ASTM Test Method for Instrumented Charpy Testing [19] requires the user to apply DFA when the difference between KV and W_t exceeds 1 J or 15% of KV, whichever is the greater.

In this paper, we aim at showing the effectiveness and usefulness of DFA by analyzing the results obtained from notched and precracked Charpy specimens tested in the framework of a recent international project (IAEA CRP8).

2 Data sets analyzed

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" [20].

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 [21].

Within this Topic Area, two international intercomparison studies were organized:

- an interlaboratory comparison of instrumented forces and energies using European Charpy verification specimens (ERM) of the high-energy level;
- a round robin exercise for the measurement of the dynamic Master Curve reference temperature from impact toughness tests on precracked Charpy specimens of a typical RPV steel [22].

2.1 Interlaboratory comparison of ERM Charpy specimens

In order to verify the calibration of the instrumented strikers used by CRP8 participants in the round robin exercise, an interlaboratory comparison was conducted based on characteristic forces measured from instrumented impact tests. Each laboratory tested, at room temperature, two Charpy specimens from the high-energy European reference material (ERM, KV ~ 150 J). Participants were required to use the same experimental setup (pendulum and instrumented striker) as in the dynamic Master Curve round robin and to report, for each specimen tested, values of force at general yield (F_{gy}) and maximum force (F_m), as well as absorbed energy from the instrumented curve (W_t) and from the machine encoder (KV).

The original values reported by the participants for F_{gy} and F_m are shown in Figures 2 and 3 respectively. The mean values are 18.8 kN for F_{gy} and 24.8 kN for F_m. Relative standard deviations are 9% for F_{gy} and 12% for F_m.

The scatter obtained from forces at general yield can be considered "normal", considering that several factors contribute to the variability of results:

(a) material inhomogeneity (that can be considered small in the case of a reference material);
(b) differences between pendulum machines;
(c) differences between instrumented strikers (design and calibration);
(d) uncertainty in determining the general yield point on the instrumented trace, using different possible approaches ("naked eye" judgment, various fitting routines, a combination of both, etc…).

On the other hand, the large scatter observed for maximum forces (12% of the mean value) is unexpected, as well as the fact that it is significantly higher than the standard deviation of F_{gy} (9% of the mean value). Indeed, the procedure for determining F_m in the case of ductile behavior (i.e. the value corresponding to the maximum of the fitted curve through the oscillations following the onset of yield for the entire ligament) leaves little room for subjective interpretations, and the contribution of item (d) above should become minor.

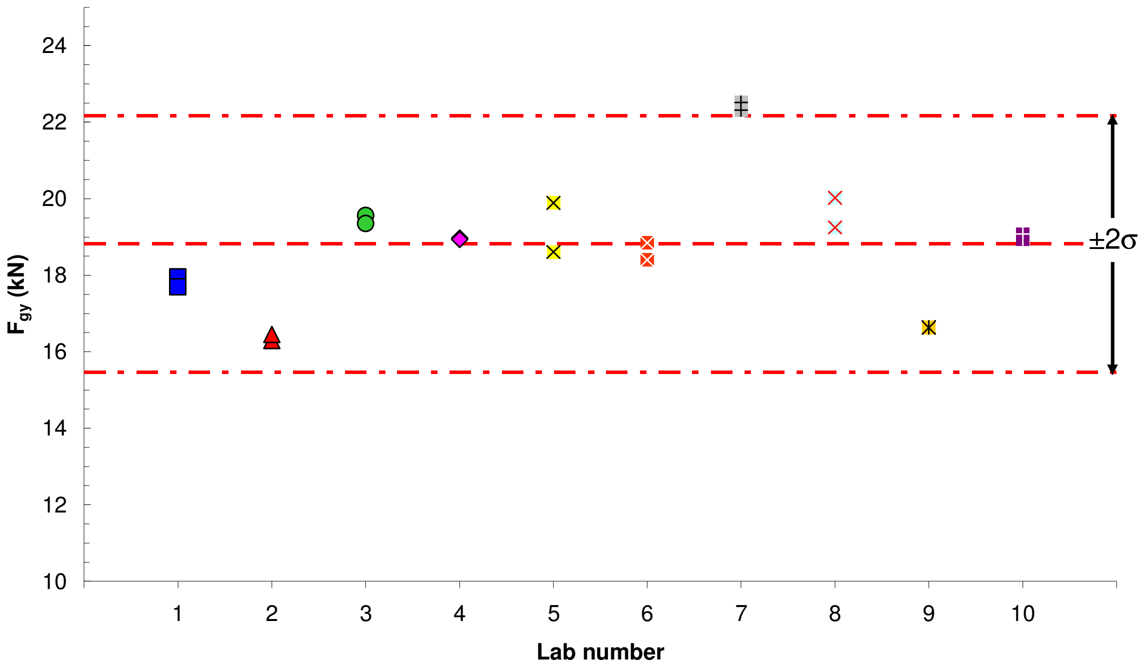

Figure 2 – Forces at general yield reported by the participants.

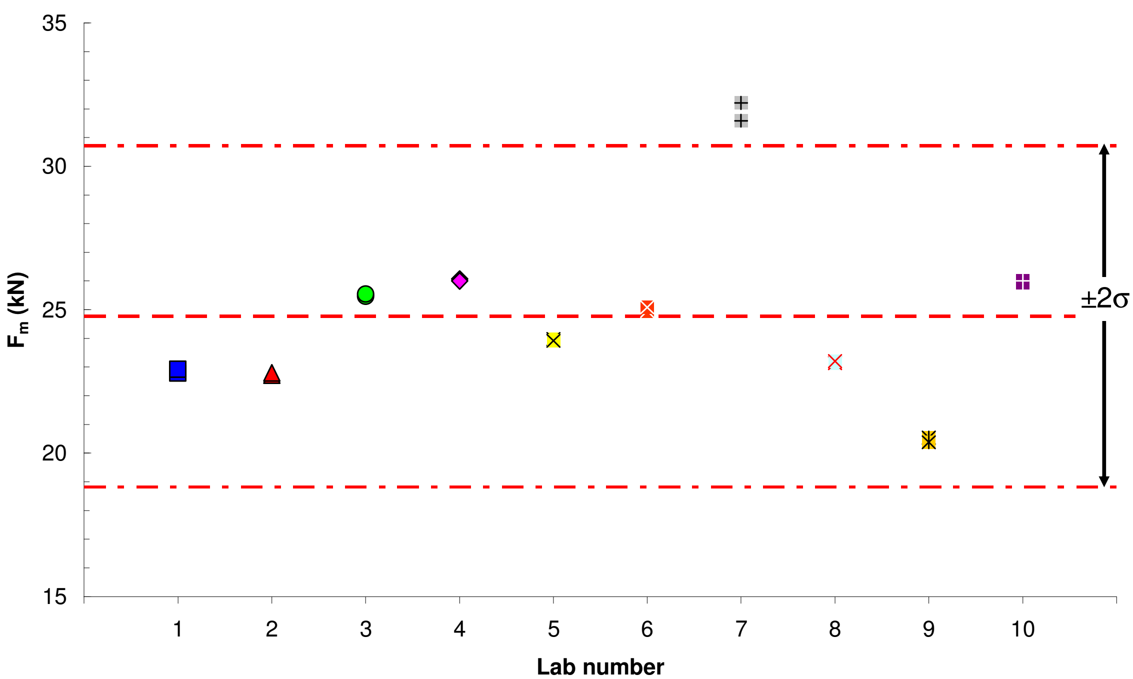

Figure 3 – Maximum forces reported by the participants.

Examination of Figures 2 and 3 also reveals that lab 7 is an outlier, with values of both F_{gy} and F_m falling outside the 95% confidence bounds (±2σ) around the mean values. This is confirmed by the Grubbs' test, also known as ESD (extreme studentized deviate), that can be used on small data sets to determine whether the most extreme value is a significant outlier from the rest. Using for each laboratory the average value of the two tests performed, for lab 7 the calculated values of Z[1] are 2.1163 (F_{gy}) and 2.3358 for (F_m). These are respectively lower and slightly higher than the critical value of Z = 2.29 corresponding to the 95% significance level (two-sided). In layman's terms, we can say that lab 7 is an outlier for F_m and a "quasi-outlier" for F_{gy}.

2.2 Round robin exercise on impact toughness measurements from precracked Charpy specimens

The same 10 laboratories that participated in the CRP8 intercomparison of instrumented Charpy results performed dynamic toughness tests at impact loading rates on precracked Charpy (PCC) specimens [22]. Each participant tested 10 PCC specimens of a typical RPV steel of the A533B cl.1 type, denominated JRQ [23], and measured the dynamic Master Curve reference temperature following ASTM E1921-05. The chemical composition and the room temperature tensile properties of the JRQ steel 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

The values of reference temperature $T_{0,d}$ reported by the participants are shown in Figure 4. This temperature corresponds to a median dynamic toughness value of 100 MPa√m for a specimen having a reference thickness 1 in. = 25.4 mm [24].

The mean value of $T_{0,d}$ is -2.2°C and the standard deviation is 8.31°C. The mean value is in close agreement with the outcome of the overall Master Curve analysis (-4.0°C).
Once again, lab 7 provides a result which falls outside the 95% confidence range of the overall dynamic reference temperature, calculated by performing an overall Master Curve analysis on all the toughness values measured by the participants. The Grubbs' test indicates that the Z value for lab 7 (2.192) is quite close to the critical value (2.29) at the 95% significance level. Another "quasi-outlier", in other words.

[1] The ratio Z is calculated as the absolute difference between the outlier and the mean divided by the standard deviation. The mean and the standard deviation are calculated using all values, including the suspected outlier. If Z is higher than the critical value corresponding to the number of values in the data set (10 in our case), then there is less than a 5% chance that an outlier so far from the others (in either direction) would be encountered by chance alone, if all the data were sampled from a single Gaussian distribution.

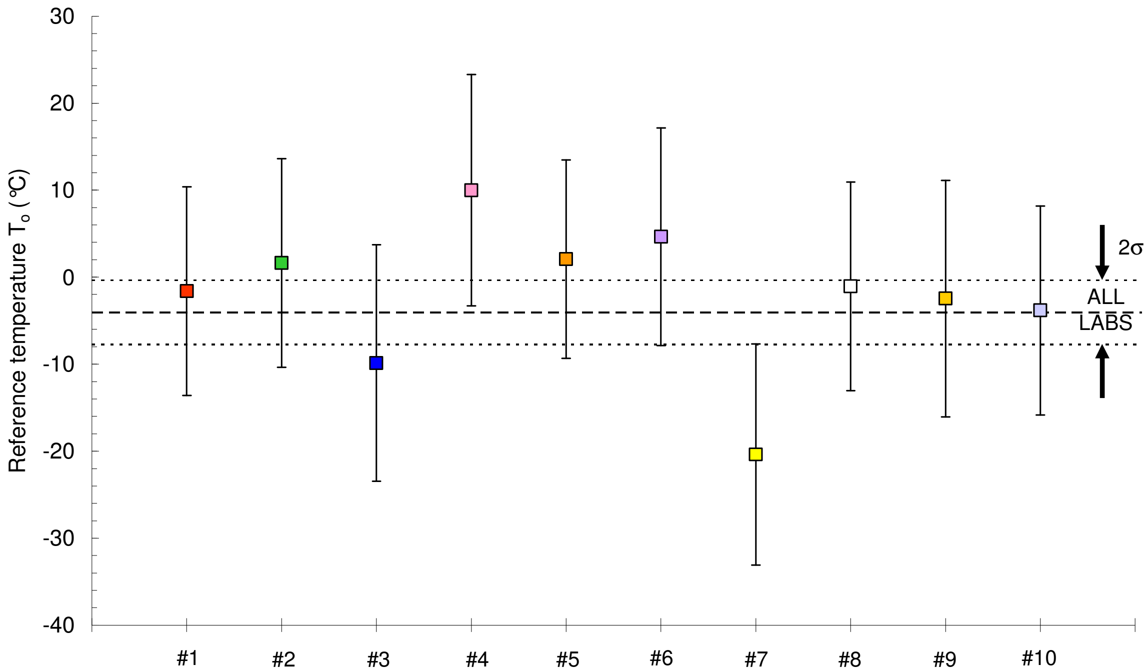

Figure 4 – Dynamic reference temperature values reported by the participants. Error bars correspond to ±2σ. The dashed line corresponds to $T_{0,d}$ obtained from an overall Master Curve analysis.

3 Application of DFA

3.1 Instrumented Charpy Data

Each instrumented force value from the intercomparison study (F_{gy} and F_m) was adjusted by imposing equivalence between W_t and KV. The results are shown in Figures 5 and 6. The mean values decrease from 18.8 to 18.3 kN for F_{gy} and from 24.8 to 24.0 kN for F_m. The standard deviation for F_{gy} is reduced from 9% to 6% and for F_m drops dramatically from 12% to 3%, i.e. below the value for general yield forces. Furthermore, the anomaly represented by lab 7 totally vanishes. Grubbs' test confirms that no outlier is present in the dynamically adjusted data set.

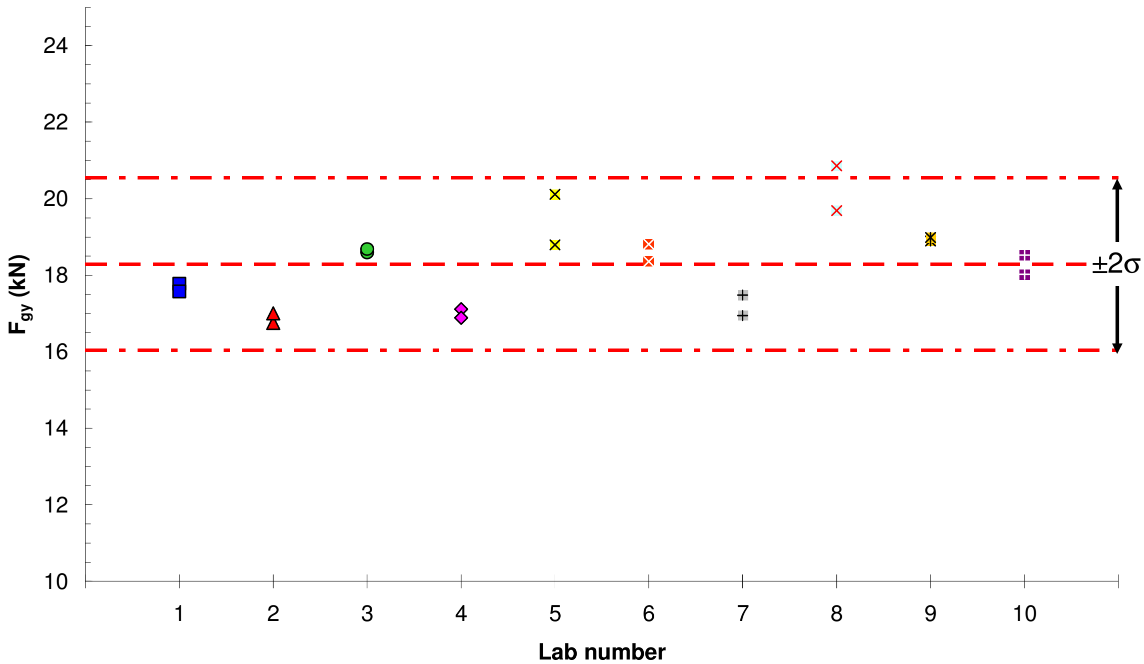

Figure 5 – Forces at general yield after DFA application.

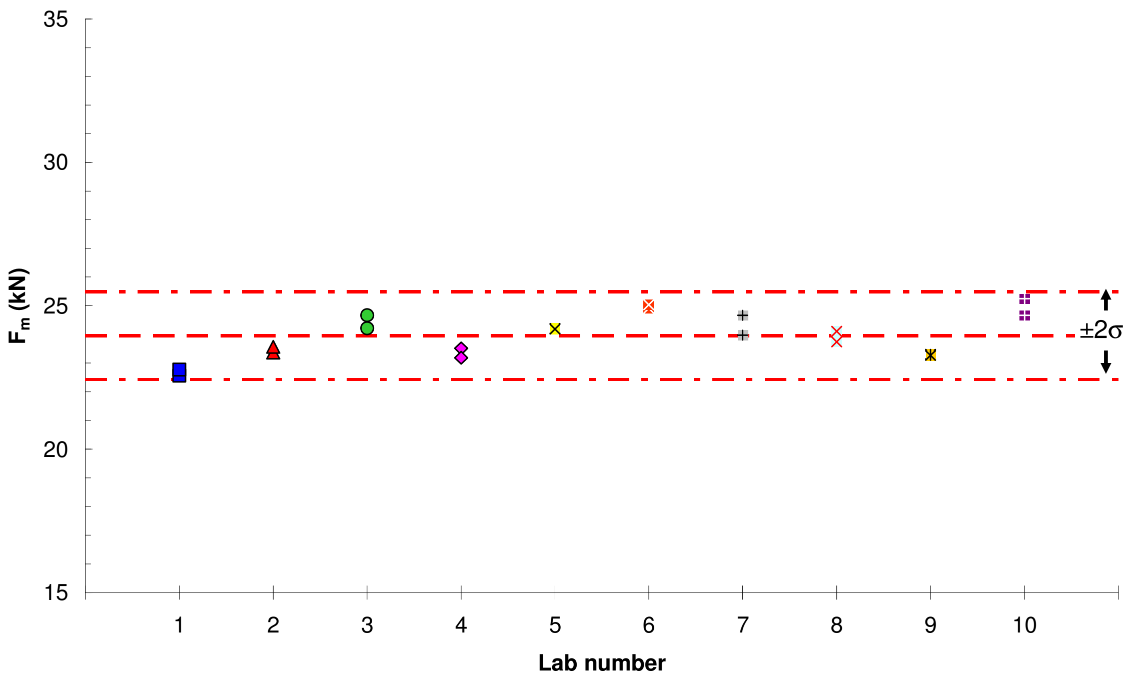

Figure 6 – Forces at general yield after DFA application.

3.2 Dynamic Toughness Data

Each dynamic fracture toughness value (K_{Jd}) was dynamically adjusted by reanalyzing the original force/displacement curve and imposing equivalence between W_t and KV. Individual and overall dynamic reference temperatures were then recalculated according to the Master Curve procedure in ASTM E 1921-05 and are shown in Figure 7 with ±2σ error bars.

The mean and the overall dynamic Master Curve reference temperatures increase from -2.2°C and -4.0°C (before DFA) to -0.7°C and 1.1°C (after DFA). The standard deviation of the individual $T_{0,d}$ values decreases slightly (from 8.31°C to 7.88°C). Lab 7 provides now a result in line with the general trend. However, a new outlier datum appears (lab 4), as confirmed by Grubbs' test (Z = 2.356). The reason for the occurrence of this new outlier is not clear, since lab 4 does not exhibit an anomalous behavior in Figures 5 or 6.

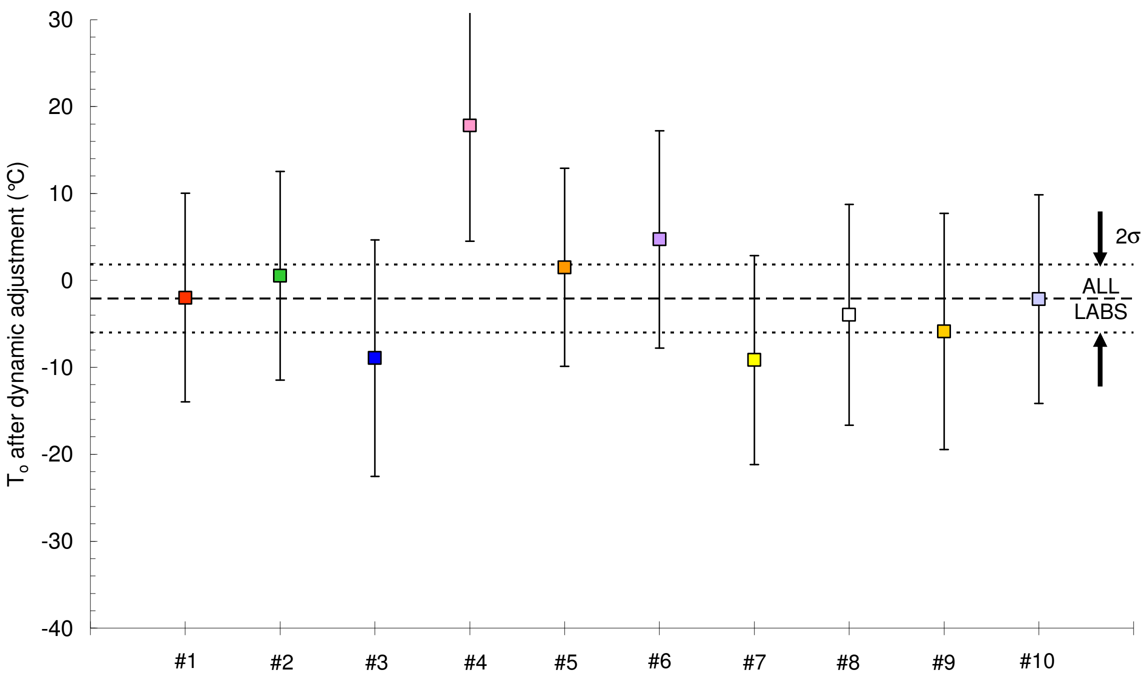

Figure 7 – Dynamic reference temperature values reported by the participants after DFA application.

3.3 Effect on Between-Laboratory Reproducibility

The effect of DFA on the scatter of the force intercomparison results was also assessed using a different approach. A statistical analysis was performed in accordance with ASTM E691-05, in order to determine the between-laboratory reproducibility of the F_{gy} and F_m data sets.

Reproducibility deals with the variability between individual test results obtained in different laboratories. The between-laboratory consistency statistic, *h,* is calculated as:

$$h = \frac{d}{s_{\overline{X}}} \tag{2}$$

where *d* is the deviation of the laboratory average from the average of the laboratory averages and $s_{\overline{X}}$ is the standard deviation of the laboratory averages. The critical values of *h* at the 95% significance level only depend on the number of labs, and in this case correspond to ± 2.29.

Based on the original results supplied by the participants, lab 7 is close to the critical value for F_{gy} (2.13) and exceeds it for F_m (2.32). The reproducibility standard deviations for the original intercomparison results, s_R, equal 1.75 kN for F_{gy} and 3.02 kN for F_m. Once again, note that s_R for F_m is almost twice the value calculated for F_{gy}.

After DFA is applied, all the recalculated values for the *h* statistics are well inside the range corresponding to the 95% significance level, including lab 7 (h = -0.97 for F_{gy} and h = 0.48 for F_m). The largest absolute values after DFA are 1.78 for lab 8 (F_{gy}) and -1.70 for lab 1 (F_m). The reproducibility standard deviations drop by 33% to 1.17 kN for F_{gy} and by as much as 74% to 0.79 kN for F_m.

The ASTM E 691-05 analyses therefore fully substantiate the effectiveness of DFA in drastically reducing the scatter of the force intercomparison results.

4 Discussion

As previously mentioned, the following factors contribute to the between-laboratory variability of data sets consisting of instrumented Charpy results:

(a) material;
(b) test machine (pendulum);
(c) instrumented striker;
(d) analytical procedures/fitting routines.

Considering the values of maximum force from the IAEA CRP8 intercomparison exercise, (a) and (d) represent minor contributions for the reasons previously stated, and could be estimated of the order of 1% each. The contribution of the test machine is a priori unknown. However, considering that the only factor affected by DFA is obviously (c), we can quantify the weight of this contribution as the difference between the standard deviation before and after the application of DFA, that is 9% (from 12% to 3%). This leaves only 1% for the factor related to test machine variability, i.e. the same magnitude as material and analytical procedures.

This shows that for the F_m data set under investigation, the variability related to the instrumented striker is by far the largest contribution, almost one order of magnitude greater than any other contributing factor.

In the case of general yield forces, although it's safe to say that the uncertainty caused by factor (d) is larger than for F_m, its actual weight is generally difficult to estimate. However, since in the case under examination, the striker factor contributes for 3% (from 9% before DFA to 6% after DFA) and assuming the same weight of factors (a) and (b) (~ 1%), one obtains a contribution of approximately 4% for the analytical procedure.

5 Conclusions

This paper shows that the dynamic force adjustment (DFA) is very effective in drastically reducing the scatter of instrumented Charpy results obtained in the framework of a Coordinated Research Project (CRP8) of the International Atomic Energy Agency (IAEA).

The standard deviation of general yield forces reported by 10 participants decreases from 9% to 6% of the mean value. For maximum forces, the reduction is even more significant, from 12% to 3%. Accordingly, the between-laboratory reproducibility standard deviation is reduced after DFA application from 1.75 to 1.17 kN for F_{gy} and from 3.02 to 0.79 kN for F_m.

The effects of DFA on dynamic Master Curve reference temperatures measured by the same laboratories using precracked Charpy specimens are less significant. Nevertheless, a reduction of the standard deviation from 8.31°C to 7.88°C is observed.

For maximum force measurements, it is clear that the calibration of the instrumented striker is by far the largest contribution to the between-laboratory scatter in an interlaboratory study. In terms of general yield forces, its weight is probably equivalent to that of the analytical procedure used to determine the general yield point on the instrumented trace.

It would be useful to apply DFA to the results of other instrumented Charpy round robin exercises, in order to assess whether the findings of this investigation are of general applicability.

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