# NEW APPROACH TO MEASUREMENT OF IMPACT CHARACTERISTICS OF BRITTLE MATERIALS

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ABSTRACT

A dynamic Fracture Energy-Drop Weight Test (DFE-DWT) is described. This machine is the dynamic equivalent of the ASTM flexural test and is the linear equivalent of the Charpy impact test. A convenient method of data reduction is explained with the aid of some typical results for two thermosetting resins. An impact mass is dropped from a preselected height, the specimen fractures, and the energy remaining after fracture is determined by measuring the indentation of a material which has previously been calibrated. One may vary both the impact weight and the drop height to obtain an energy large enough to break the materials of interest.

A Comparison of DFE-DWT with the Charpy Impact Test

| | Charpy Impact Machine | DFE-DWT Machine |
|---|---|---|
| 1. Impact Velocity | 0-11.5 ft/s (3.51 m/s) | 0-18.7 ft/s (5.7 m/s) |
| 2. Span | 4 in. (101.6 mm) Fixed | 3-6 in. (76.2-152.4 mm) Variable |
| 3. Energy Range | 0-192 in·lb (2.215 m·kg) | 0-500 in·lb (5.76 m·kg) |
| 4. Machine Cost | Low | Very low |
| 5. Impact Mass | Yes, variable by changing impact arm | Yes, continuously variable by adding or removing shot from hollow impact head |
| 6. ASTM Radii | No | Yes |

KEYWORDS

Fracture, impact energy, thermosetting resins, impact testing, plastics.

NOMENCLATURE

| Symbol | Meaning | Units |
|---|---|---|
| t | Remaining solder thickness after impact | mils (0.001) in |
| $U_f$ | Energy for fracture | in·lb |
| W | Impact weight | lb |
| H | Distance from impact nose ready position to brass impact disc | |
| h | Distance between the impact nose ready position and the test specimen | |
| $U_r$ | Energy remaining after sample fracture | in·lb |
| $U_{max}$ | Energy absorption capability of mid-span outer fibers | $in \cdot lb/in^3$ |
| b, d, ℓ | Specimen width, depth, span | in |
| $R_1$ | Notch or scratch sensitivity ratio | |
| σ | Unbiased standard deviation | |
| $U_{ff}$ | Energy for fracture of flaw-free specimen surfaces | in·lb |
| $U_{ns}$ | Energy for fracture of notched specimen surfaces | in·lb |
| $R_2$ | Fracture energy notch sensitivity ratio $U_{ns}/U_{ff}$ | |
| (DFE-DWT) | Dynamic Fracture Energy-Drop Weight Test | |

Appropriate Standard International Units are obtained by substituting m for in and Kg for lb.

## INTRODUCTION

Recent literature indicates a growing interest in impact testing and a need for more reliable and standardized methods of material evaluation. It is not the intent of this paper to review the various methods available, but to describe an apparatus which is the dynamic equivalent of ASTM D790 Flexural Testing [1].

This paper will describe a means of determining the total energy of fracture and simultaneously the maximum energy absorption density capability for brittle materials.

Figure 1 illustrates schematically the basic impact "machine", the method of mechanical loading, and specimen geometry. The specimen dimensions may be varied, however, one should conform with the ASTM recommended span to depth ratio in the range of 16 to 40 to avoid running a short beam shear test. As indicated in Fig. 1, the loading is a standard three point bending with line loading.

An impact mass is dropped from a preselected height, the specimen fractures, and the energy remaining after fracture is determined by measuring the indentation of a material which has previously been calibrated. For plastics, 3/16 in (4.76 mm) OD solder is an inexpensive and reliable, and readily available, material. Other materials may be used such as aluminum [2,3]. Periodic diameter checks and calibration checks will avoid errors due to solder variability or mix up of solder grades.

The impact mass is hollow to permit adding lead or steel shot, giving the weight desired. Empty space within the mass is filled with crumpled paper to prevent movement of the shot during impact. Both one and two pound weights have been used. The impact mass fits loosely within a slotted steel pipe. A bolt attached to the impact mass extends through the pipe slot to guarantee line loading perpendicular to the sample length. Four specimen holders to guides are attached to the test specimen supports which position the test specimen perpendicular to the supports. Both specimen supports and the impact nose are machined to a 3/16 in (4.763 mm) radius as suggested in ASTM D790-70.



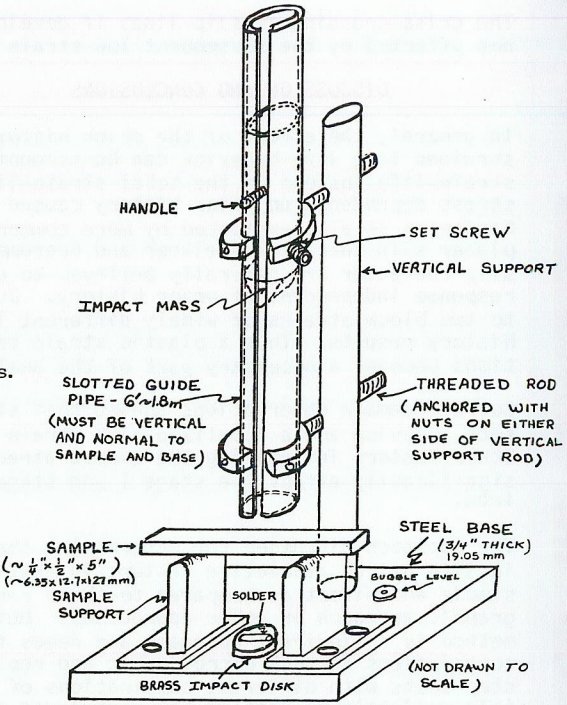


Fig. 1. DFE-DWT schematic.

## SPECIMEN PREPARATION

For plastics, a water saw fitted with a 0.080 in (2.032 mm) carborundum blade, has proven to be adequate for machining test materials. Both polishing and notching should significantly reduce data scatter and the problem of a large standard deviation can be treated by increasing the number of test specimen.

For a 3 in (76.2 mm) span a convenient specimen size is 0.25 x 0.50 x 5 in (6.35 x 12.7 x 127 mm).

## DYNAMIC FRACTURE ENERGY - DROP WEIGHT TEST (DFE-DWT):

The DFE-DWT can be calibrated in approximately one hour and requires only occasional calibration checks.

The impact weight W is dropped on 1.4 in (35.6 mm) lengths of solder from various heights to completely cover the range of interest. The solder must lie parallel to the length of a test specimen if it were in position. Two small pieces of Duxseal provide a holder for the solder on the brass impact disk.

Calibration energy is equal to WH. The impacted solder may be easily measured with a common ball micrometer. A plot of energy (U) versus remaining solder thickness (t) is made to establish the calibration curve (see Figs. 2, 3 and 5). Note that H is the distance between the impact weight in the "ready position" and the brass impact disk, while h is the distance between the impact weight in the "ready position" and the test specimen.

No lubrication of any type was used within the column nor is it recommended. The difference between calibration with and without lubrication was within the experimental uncertainty.

## TEST METHOD

One may vary both the impact weight and the drop height to obtain an energy large enough to break the materials of interest. The velocity at impact is $\sqrt{2gh}$. If a specified velocity is required, then h is fixed and the weight must be adjusted to obtain an initial impact energy large enough to fracture all specimens.

A virgin 1.4 in (35.6 mm) length of straight solder must be in position. The impact disk is made of brass to avoid damage to the impact nose in the event that the operator fails to place solder in position. The brass disk may be resurfaced on a belt sander if this error occurs. The test specimen is positioned between the holders. A stop in the form of a bolt or clamp may be used to set the height of drop at H. One raises the impact head by hand or with a yardstick to the ready position (with the cage door closed) and releases the weight. Safety glasses are highly recommended.

The impacted solder is measured with the ball micrometer. This thickness "t" will correspond to some energy on the calibration curve (Figs. 2 and 3).

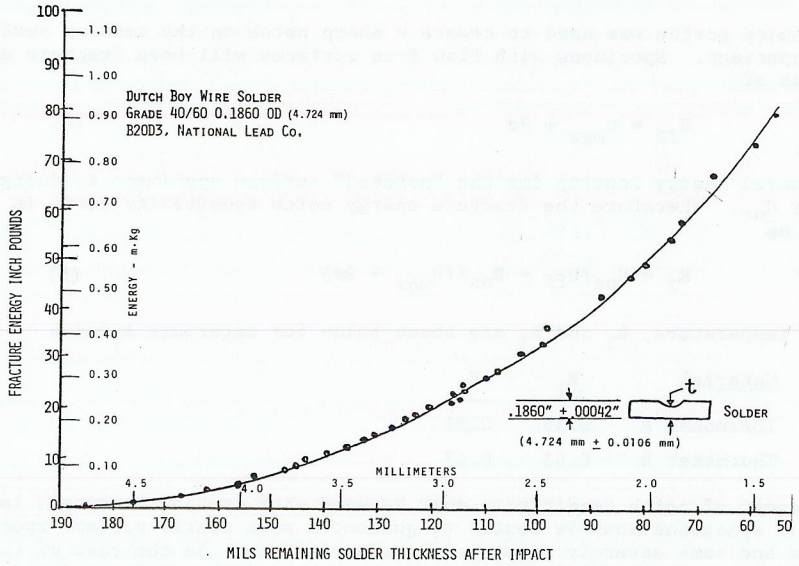


Fig. 2. Fracture energy calibartion curve.

Energy for fracture is: $$U_f = WH - U_r \quad . \qquad (1)$$

Where H is the distance from the impact nose ready position to the brass impact disk. $U_r$ is the energy remaining after sample fracture as determined from measurement of the impacted solder. Note that since the upper specimen surface is approximately 4.4 in (112 mm) from the brass impact disk, the



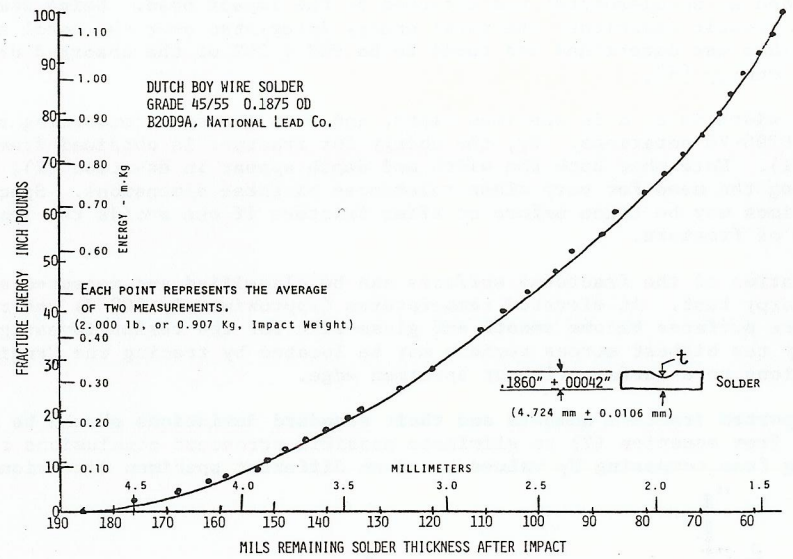


Fig. 3. Fracture energy calibration curve.

lowest possible $U_r$ measured is $U_r \approx 4.4$ in lb/lb (0.112 m·kg/kg) of striking weight or 8.8 in lb (0.101 m·Kg) for a 2.0 lb (0.907 Kg) impact head. If the impacted solder does not present a smooth 0.19 in (4.83 mm) radius impact surface, a portion of the fractured specimen interfered with indentation and the test is invalid. This problem is extremely rare.

The number of specimens depend on the standard deviation or the confidence one imposes on the mean. In any case, if test specimens are unnotched and unpolished, at least five specimens should be used. For the thermosetting resins investigated six tests result in less than 20% uncertainty in the mean fracture energy with a 90% confidence interval.

Temperature testing may be easily done since no significant change in the specimen temperature occurs before the test is complete. Temperature tests from liquid nitrogen temperature (-196° C) to 120° C have been made with no difficulty. Specimens were immersed in the low temperature fluids for at least fifteen minutes and removed with tongs for testing. Only a few seconds elapse during the test, so that changes in the test specimen temperature prior to fracture were minimized.

## DATA ANALYSIS

Since one is concerned with brittle fracture, the fracture stresses are very close or equal to the yield stresses. The mid-span outer fiber energy absorption capability is [4]:

$$U_{max} = \frac{9}{bd\ell}\,(U_f) \text{ in·lb/in}^3 \qquad (2)$$

The validity of the linear elastic assumption has been tested for fourteen epoxies. In a similar DFE-DWT machine, specimens were fitted with strain

gages and an accelerometer was attached to the impact head. Using standard linear elastic equations, the total energy integrated over the total specimen volume was determined and found to be 90% ± 10% of the absorbed drop height energy [5].

Sample width is b, d is specimen depth, and ℓ is the span conforming to ASTM- D790-70 notations. $U_f$, the energy for fracture is obtained from equation (1). Note that both the width and depth appear in equation (2), eliminating the need for very close tolerances on these dimensions. Specimen dimensions may be taken before or after fracture if one avoids the immediate region of fracture.

Examination of the fractured surfaces can be classified and measured as in the Charpy test. At elevated temperatures (approximately 80° C) the rough fracture surfaces become smooth and glass-like for the resins investigated. Usually the highest stress regions may be located by tracing the "radial" striations to a surface flaw or specimen edge.

All reported fracture numbers and their standard deviations should be obtained from equation (2) to eliminate possible erroneous conclusions resulting from comparing $U_f$ values based on different specimen dimensions.

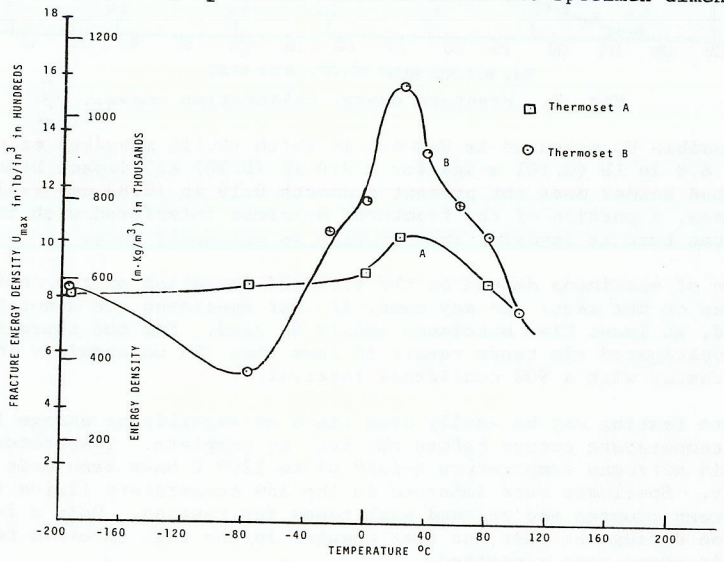


Fig. 4. Fracture energy density vs. temperature.

## TYPICAL FRACTURE PROPERTIES OF TWO THERMOSETTING RESINS AND COMPARISON WITH CHARPY TEST

The DFE-DWT method described has been used to determine the fracture energy density versus temperature curves shown in Fig. 4. Thermoset A is relatively insensitive to temperature while Thermoset B varies between 540 and 1565 in·lb/in$^3$ (379,600 - 1,100,000 m·Kg/m$^3$) over the temperature range of -196° C to 100° C. The operating temperature of interest would dictate a choice between these materials. Table 1 tabulates the data used for Fig. 4.



Standard deviation (unbiased) is on the average 23% of the mean with a range of 9% to a high of 43%. These large standard deviations should not be alarming since no polishing or machine notching was performed on any of the test specimens. Since all specimens have shallow saw marks on the upper and lower surfaces, the size of the standard deviation gives some indication of the fracture energy "notch" or scratch sensitivity ratio. That is, $U_{max} + 2\sigma$ represents a relatively flaw free sample and $U_{max} - 2\sigma$ represents a specimen with severe surface defects. The ratio is defined as

TABLE 1 Fracture Energy Density Data in·lb/in$^3$
(To convert in·lb/in$^3$ to m·Kg/m$^3$ multiply by 703)

| Temp. °C | Thermoset A | | Thermoset B | |
|---|---|---|---|---|
| | $U_{max} \pm \sigma$ | σ(%) | $U_{max} \pm \sigma$ | σ(%) |
| 100 | --- | -- | 768 ± 188 | ±24% |
| 80 | 862 ± 201 | ±23% | 1035 ± 147 | ±14% |
| 24 | 1039 ± 250 | ±24% | 1578 ± 179 | ±11% |
| 0 | 906 ± 309 | ±34% | 1164 ± 495 | ±43% |
| -25 | --- | -- | 1059 ± 117 | ±11% |
| -78.5 | 862 ± 86 | ±10% | 543 ± 190 | ±35% |
| -196 | 813 ± 257 | ±32% | 836 ± 202 | ±24% |

$$R_1 = \frac{U_{max} - 2\sigma}{U_{max} + 2\sigma} \qquad (3)$$

where α is the unbiased standard deviation. Another approach to determining $R_1$ was used to check this concept.

A very sharp scribe was used to create a sharp notch on the tension surface of the specimen. Specimens with flaw free surfaces will have fracture energy densities of

$$U_{ff} = U_{max} + 2\sigma \qquad (4)$$

The measured energy density for the "notched" surface specimens is designated as $U_{ns}$. Therefore the fracture energy notch sensitivity ratio is defined as

$$R_2 = U_{ns}/U_{ff} = U_{ns}/(U_{max} + 2\sigma) \qquad (5)$$

At room temperature, $R_1$ and $R_2$ are shown below for materials A and B.

| Material | $R_1$ | $R_2$ |
|---|---|---|
| Thermoset A | 0.35 | 0.31 |
| Thermoset B | 0.63 | 0.27 |

This concept of notch sensitivity must be used with caution because a large number of specimens must be tested to guarantee some nearly perfect specimen surfaces and some severely scratched sample surfaces. In the case of thermoset B, $R_1 >> R_2$, this probably indicates that none of the five specimens tested had nearly perfect surfaces or contained severe surface flaws.

Instrumentation refers to attaching strain gages to the tension face of the specimen and mounting an accelerometer on the impact head to monitor strain and force during the impact. Good data are obtained only when the impact energy is greater than that required to fracture. Dropping the impact mass from successively increasing heights yields good strain and force data.

A comparison of the advantages and disadvantages of the DFE-DWT with the Charpy Impact Test is shown in Table 2. The desirability of this new approach to impact testing is evident. Tresh [6] states "that the pendulum type of impact test when used on brittle materials produces complex dynamic effects, and the results of such tests must be used with caution."

TABLE 2 A Comparison of DFE-DWT With the Charpy Impact Test.

| | | Charpy Impact Machine | DFE-DWT Machine |
|---|---|---|---|
| 1. | Impact Velocity | 0-11.5 ft/s (3.51 m/s) | 0-18.7 ft/s (5.7 m/s) |
| 2. | Measurement | Total Energy only | Total Energy only |
| 3. | Span | 4 in fixed (101.6 mm) | 3-6 in (76.2-152.4 mm) |
| 4. | Energy Range | 0-192 in·lb (2.215 m·Kg) | 0-500 in·lb (5.76 m·Kg) |
| 5. | Machine Cost | Low | Very low |
| 6. | ASTM Radii | No | Yes |
| 7. | Impact Mass Variation | Yes, variable by changing impact arm (difficult) | Yes, continuously variable by adding or removing shot from hollow impact head (easy) |
| 8. | Instrumentation | Yes, possible | Yes, possible |
| 9. | Temp. testing | Yes, easy | Yes, easy |
| 10. | Time for test | Short | Short |
| 11. | Cost per test | Low | Low |

The Charpy machine is available in various sizes. That described above is the table top 16 ft·lb (2.215 m·Kg) version used for plastics (ASTM-D256).

Impact velocity may be extended beyond the 18.7 ft/s (5.7 m/s) level by using a longer guide pipe in the DFE-DWT machine. The maximum velocity for Charpy machine described is 11.5 ft/s (3.51 m/s).

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