Instrumented drop weight tear testing

An instrumented drop weight tear tester augments a basic machine by measuring the force that the hammer applies to the specimen to break it. From this measure of force as a function of time, displacement and energy curves can be obtained from which it is possible to identify the point on the force curve where crack initiation occurs, and from this calculate separate values for initiation energy and propagation energy.

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The drop weight tear test (DWTT) has been in use for more than 40 years as a practical laboratory-scale way of ensuring that steel used in the manufacture of line-pipe is not subject to brittle failure when in service. It is one of a battery of tests that assess the suitability of steel for a particular application, another of which is the Charpy V-notch (CVN) test, from which the upper shelf energy (USE) has commonly been used as a measure of ductile fracture resistance.

Since the introduction of the DWTT, material requirements have significantly increased. In particular, demands for higher operating pressures of pipelines and use of larger diameters have driven the development of higher strength steels. Forty years ago the work that led to the DWTT was done on X52 steel (360MPa yield strength). Improvements in thermo-mechanical processing have yielded increases of approximately 10,000psi per decade, to the point where the state-of-the-art is now X100 steels, and the use of X120 steels is being considered.

This development in material technology has placed substantial demands on conventional test techniques and the relevance of some results has been drawn into question. Since a DWT tester represents a significant investment both in terms of capital cost and operator training, it is important that any equipment being specified now should have the flexibility and the capacity to cover developments in test methodology and the mechanical properties of materials for the expected service life of the apparatus – ten years or more. To that end, this article examines issues concerning the measurement of fracture toughness of steel and, in particular, the use of high-capacity instrumented DWT testers.

BRITTLE FRACTURE

Avoidance of brittle behaviour in pipeline steel is of paramount importance to manufacturers. Originally, materials were characterised by the so-called Athens test, a full-scale burst test consisting of a test section about 200m in length pressurised with natural gas. The

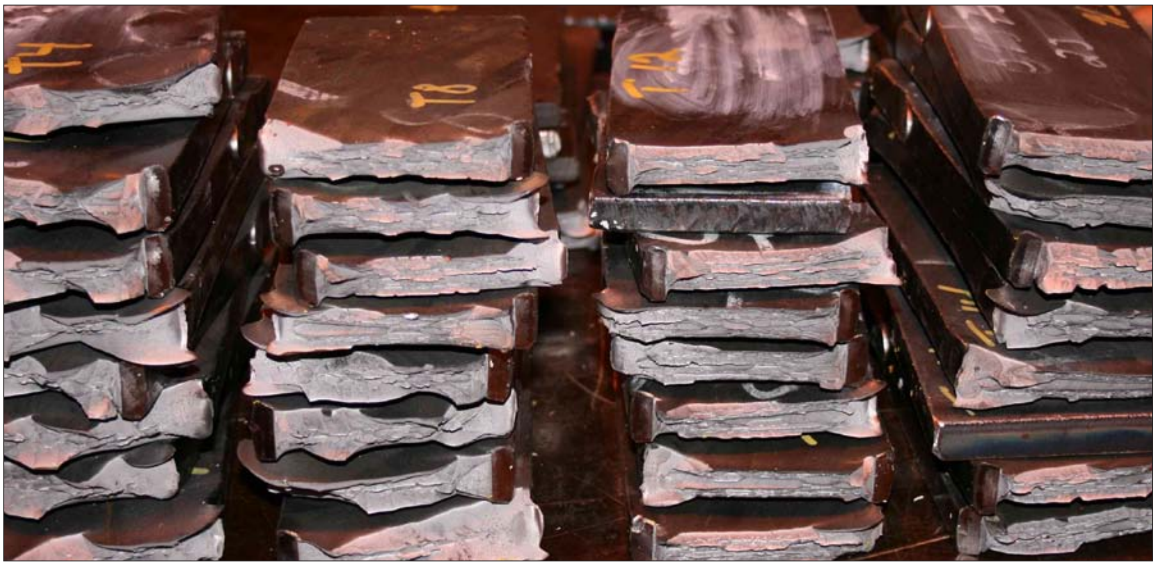

Fig 1 **Fracture surfaces of tested specimens**

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Fig 2 **Imatek DWTT with 25,000J capacity**

need for a practical, laboratory-scale test was recognised and subsequent work (notably by the Batelle Memorial Institute) resulted in the DWTT, which was adopted by the American Petroleum Institute (API) in 1965 as recommended practice 5L3.

The DWTT involves cutting a full-thickness specimen from the wall of the pipe and putting a notch in it to act as a stress raiser. The test specimen is supported at either end, then hit in the centre, on the edge opposite the notch, by a hammer attached to a falling weight, breaking it in two. The broken surfaces are then inspected, and the percentage of the surface that shows 'shear' (or ductile) fracture, as opposed to 'cleavage' (or brittle) fracture, is assessed. As a quality assurance test, this is usually done at a single specific temperature, and a minimum percentage shear area (commonly 85%) is used as the pass/fail criterion. *Figure 1* shows a selection of broken test piece fracture surfaces.

The original Batelle work, and investigations done since (at Centro Sviluppo Materiali in Rome, among other institutions), have shown good correlation between DWTT results and the results of the burst test up to at least X100 grades of steel. Further work on even stronger grades remains to be done.

While being a well-founded, widely used test, there are a number of minor problems with the DWTT. The first is that it is rather labour-intensive, and determination of the percentage shear area is a process that is difficult to automate. Another difficulty that has been observed is that some highly ductile steels show abnormal fracture appearance, which leads to difficulty applying the minimum shear area criterion.

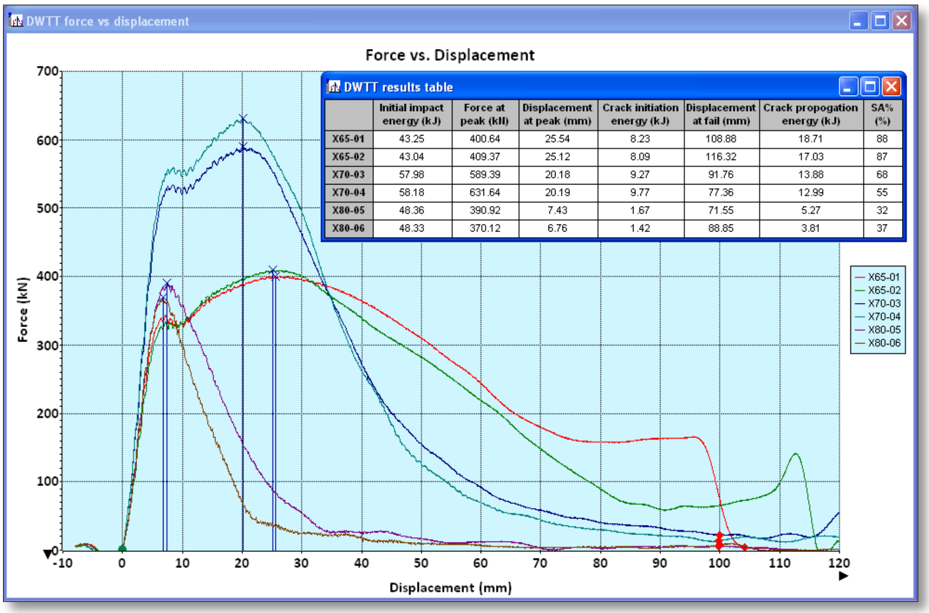
An instrumented DWT tester *(*see *Figure 2)* augments the basic apparatus by measuring the force that the hammer applies to the specimen to break it. From this measure of force (as a function of time), displacement and energy curves can be obtained *(*see *Figure 3)*. Significantly, it is possible to identify the point on the force curve where crack initiation occurs, and from this calculate separate values for initiation energy and propagation energy. Such an apparatus has the potential to circumvent both the problems described above, since it has been shown that a relationship exists between the transition temperature for DWTT crack propagation energy, and the transition temperature for 85% shear area. It will probably be quite some time before these observations feed into international standards, but there is scope for the in-house use of these test methods.

Referring to the curves in *Figure 3*, there are three grades of steel and different thicknesses shown which indicate two basic curve types. The longer, more drawn-out of the two shapes is a ductile or shear failure and the shorter/sharper shape is brittle or cleavage failure. There are three markers the software places automatically: start (green), peak (blue cross) and end of test (red) on the right-hand side. A single DWTT requires two specimens to be tested – but some batch testing requires up to 200 specimens per batch of steel to be tested.

Instrumenting a DWT tester is not a trivial matter: the forces that are generated when impacting high strength steels samples with thicknesses up to 50mm can exceed 1 MegaNewton: not only do these forces have to be measured accurately at high bandwidth, but the compliance of the apparatus needs to be low enough to make these measurements meaningful. Furthermore, the drop weight has to be precisely guided to ensure that the hammer is kept perpendicular to the plane of impact. Considering that on the higher capacity machines the total impact energy is 100,000J or more, and over its lifetime the apparatus must endure tens of thousands of such impacts, the design represents a challenging combination of heavy engineering and precision.

DUCTILE FRACTURE

As mentioned earlier, the CVN test USE has been applied as a measure of ductile fracture resistance and has provided good service. With the introduction of high-strength steels, however, the applicability of this test has



	Initial impact energy (kJ)	Force at peak (kN)	Displacement at peak (mm)	Crack initiation energy (kJ)	Displacement at fail (mm)	Crack propogation energy (kJ)	SA% (%)
X65-01	43.25	400.64	25.54	8.23	108.88	18.71	88
X65-02	43.04	409.37	25.12	8.09	116.32	17.03	87
X70-03	57.98	589.39	20.18	9.27	91.76	13.88	68
X70-04	58.18	631.64	20.19	9.77	77.36	12.99	55
X80-05	48.36	390.92	7.43	1.67	71.55	5.27	32
X80-06	48.33	370.12	6.76	1.42	88.85	3.81	37

▲ Fig 3 **Examples of equipment data output**

been called into question, and research has shown that Charpy energies above 150J are not representative for ductile fracture resistance. The problem with using the CVN test for high-strength specimens is that the crack initiation energy is very high compared to the total test energy; indeed, sometimes it is greater than the available impact energy, and the specimen simply bends instead of cracking.

To address this problem, researchers are now looking at ways of extracting energy measurements from the DWT test, since this uses more representative sample sizes (and of course there is the associated benefit of being able to use a single test to determine two material properties).

Pendulum DWT testers provide a simple way of measuring the total energy absorbed by a specimen, and are successful, up to a point. However, when used with very high-strength steels they suffer the same failing as the CVN test: with a single measurement it is impossible to separate the plastic deformation, crack initiation and crack propagation contributions to this value.

Instrumented DWT testers readily provide this type of data, and crack propagation energy can be directly derived from test results. Work done by Pohang University in South Korea has demonstrated that, while Charpy USE has a very weak correlation with DWTT propagation energy, it has a very strong correlation with DWTT initiation energy, supporting the hypothesis that for high-strength steels almost all the energy in a CVN test goes into initiating the crack.

USE OF CRACK-TIP OPENING ANGLE

The breakdown in the usefulness of CVN USE as a predictor of fracture toughness has led investigators, since the 1980s, to look towards more theoretical approaches based on fracture mechanics variables such as crack-tip stress or strain, crack-tip opening displacement or crack-tip opening angle (CTOA), crack-tip force or energy release rate. Important work at the Centro Sviluppo Materiali in Rome, among other institutions, has concluded that the most appropriate variable for modelling stable crack growth is the CTOA at a specified distance from a crack tip, or CTOA_{sc} (where 'sc' stands for stable crack – as in stable crack propagation – the period/region over which the crack propagation is assessed to be stable).

There are a number of ways of measuring CTOA, one of which is direct measurement using a high-speed video camera. A well-known indirect method is the two-specimen CTOA test (TSCT). This uses absorbed energy values for multiple DWTT-like specimens with different notch depths to derive the CTOA value.

Work at Pohang University in South Korea and others has shown a strong correlation between CTOA and DWTT propagation energy – specifically, a linear relationship between the propagation energy and $\sin(2\ \text{CTOA}_{\text{sc}})$. Although more work needs to be done to validate this relationship for a range of materials and specimens, this work suggests that it is possible to make a measurement of CTOA, an important material parameter, using a single specimen in an instrumented DWT tester.

CONCLUSIONS

The addition of instrumentation to a DWT tester turns an apparatus for conducting a 40-year old quality control test into a research tool that is likely to cater for test requirements well into the future, investigating and characterising brittle and ductile fracture resistance in line-pipe steel.

By measuring the force over time that the hammer applies to the specimen to break it, displacement and energy curves can be obtained from which it is possible to identify the point on the force curve where crack initiation occurs, and from this calculate separate values for initiation energy and propagation energy. **MS**

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