The drop weight tear test (DWTT) was developed over 40 years ago as a practical laboratory-scale way of ensuring that steel for line-pipe is not subject to brittle failure while in service. An instrumented drop weight tear tester measures the amount of force required to break a specimen, and this enables calculation of separate values for initiation energy and propagation energy. DWTT is one of a battery of tests that evaluate the suitability of steel for a particular application. Another is the Charpy V-notch test, from which the “upper shelf energy” has commonly served as a measure of resistance to ductile fracture.

Since the introduction of the DWTT, materials have significantly improved. In particular, steels with much higher strength have been developed as a result of the need for higher operating pressures and larger diameters for line-pipes. Forty years ago, the work that led to the drop weight tear test was done on X52 steel (52 ksi yield strength). Advances in thermo-mechanical processing have yielded improvements of approximately 10,000 psi per decade, to the point where the state of the art is now X100 steels, and X120 steels are being considered.

Since a DWT tester represents a significant investment in terms of both capital cost and operator training, it is important that any equipment specified now have the flexibility and the capacity to cover developments in test methodology and materials for ten years or more. Therefore, this article examines issues concerning the measurement of fracture toughness of steel, and in particular high-capacity instrumented DWT testers. These issues include brittle fracture, ductile fracture, and crack-tip growth in high-strength steels.

Brittle fracture
Avoidance of brittle behavior in pipeline steel is of paramount importance. Originally, materials were characterized by the so-called Athens test, a full-scale burst test of a section about 200 m in length pressurized with natural gas. However, a practical, laboratory-scale test was needed, and subsequent work (notably by the Battelle Memorial Institute) resulted in the drop weight tear test, which was adopted by the American Petroleum Institute 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 both ends, then hit in the center, 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 the pass/fail criterion.

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

DWTT is well-founded and widely used, but it has a number of minor problems. The first is that it is rather labor-intensive, and determination of the percentage shear area is difficult to automate. Another problem is that some highly ductile steels show an abnormal fracture appearance, which leads to difficulty applying the minimum shear area criterion.

An instrumented DWT tester 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 generated. Significantly, it is possible to identify the point on the force curve at which the crack initiates, and from this to calculate separate values for initiation energy and propagation energy. Such an apparatus has the potential to circumvent both problems described above, because 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 application of these methods.

Ductile fracture

As mentioned above, Charpy V-notch test “upper shelf energy” serves as a measure of ductile fracture resistance and has provided good correlation. However, the applicability of this test to high-strength steels has been called into question, and research has shown that Charpy energies above 150 J are not representative for ductile fracture resistance.

The trouble with the Charpy test for high-strength specimens is that the crack initiation energy is very high compared to the total test energy. In fact, sometimes it is greater than the available impact energy, and the specimen simply bends instead of cracking.

To address this problem, researchers have looked at ways of extracting energy measurements from the DWT test, since it has more representative sample sizes. An associated benefit is that a single DWT test can 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. Unfortunately, with a single measurement of very high-strength steels it is impossible to separate the plastic deformation, crack initiation, and crack propagation contributions to this value. However, Instrumented DWT testers in which transducers measure force, velocity, and displacement throughout specimen failure, readily provide this type of data, and crack propagation energy can be directly derived from test results.

As an aside, work done by Pohang University in South Korea has demonstrated that while Charpy “upper shelf energy” 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 Charpy test goes into initiating the crack.

Crack tip angle

The breakdown in the usefulness of Charpy “upper shelf energy” as a predictor of fracture toughness has led investigators, since the 1980s, to look for more theoretical approaches based on fracture mechanics variables such as crack-tip stress or strain, crack-tip opening displacement (or crack-tip opening angle), crack-tip force, or energy release rate, to name just a few.

Important work at the Centro Sviluppo Materiali and other institutions, has concluded that the most appropriate variable for modeling stable crack growth is the crack tip opening angle (CTOA) at a specified distance from a crack tip, or CTOA_{sc}. In this nomenclature, “sc” stands for stable crack – as in stable crack propagation – the period/region over which the crack propagation is assessed to be stable.

CTOA can be measured in a number of ways, one of which is direct measurement by a high-speed video camera. A well known indirect method is the two-specimen CTOA test or TSCT. It is based on absorbed energy values for multiple DWTT-like specimens with different notch depths to derive the CTOA value.

Work at Pohang University and others has shown a strong correlation between CTOA and DWTT propagation energy. Researchers found a linear relationship between the propagation energy and the sine of the (2 CTOA_{sc}) angle. Although more work needs to be done to validate this relationship for a range of materials and specimens, results suggest that it is possible to make a measurement of CTOA, an important material parameter, with a single specimen in an instrumented DWT tester.

In summary, 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 meet test requirements well into the future, investigating and characterizing brittle and ductile fracture resistance in line-pipe steel.

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